



Limited Handling Qualities Evaluation of Inter-axis Control Coupling (Project Icarus)

**DAIL FIELDS, Maj, USMC
DAVID MARTEN, Maj, USAF
GIANMARCO DI LORETO, Capt, ITAF**
Project Pilots

**ROBERT KOO, Capt, USAF
JADE LEMERY, Capt, USAF
KATHERINE RYAN, Capt, USAF**
Project Engineers

JUNE 2010

TECHNICAL INFORMATION MEMORANDUM

Approved for public release; distribution is unlimited.

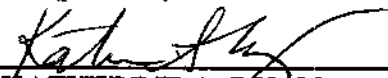
**USAF TEST PILOT SCHOOL
AIR FORCE FLIGHT TEST CENTER
EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE**

**U
S
A
F

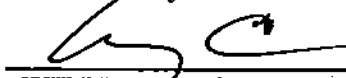
T
P
S**

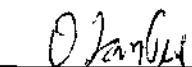
This Technical Information Memorandum, "Limited Handling Qualities Evaluation of Inter-axis Control Coupling (Project Icarus)" was submitted under job order number MT09B100 by the commandant, USAF Test Pilot School, Edwards AFB California 93524-6485.

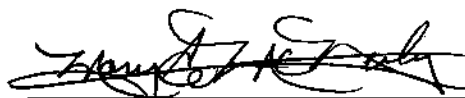
Prepared by:

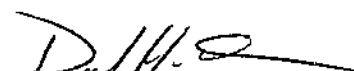

KATHERINE A. RYAN
Capt, USAF
Project Manager/Flight Test Engineer


Reviewed by:

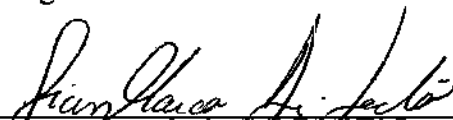

WILLIAM R. GRAY, YA-III, USAF
Staff Advisor
USAF Test Pilot School


DAIL T. FIELDS
Major, USMC
Flight Test Pilot

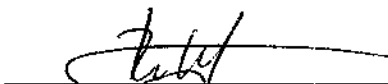

MARY E. MCNEELY, YD-II, USAF
Chief, Test Management Branch
USAF Test Pilot School



DAVID H. MARTEN
Major, USAF
Flight Test Pilot



DAVID L. VANHOY, YD-III, USAF
Technical Director
USAF Test Pilot School


GIANMARCO DI LORETO
Capt, ITAF
Flight Test Pilot

**This memorandum has been approved
for publication:**


ROBERT KOO
Capt, USAF
Flight Test Engineer


JADE M. LEMERY
Capt, USAF
Flight Test Engineer


NOEL ZAMOT
Colonel, USAF
Commandant, USAF Test Pilot School

JAN 19 2011

REPORT DOCUMENTATION PAGE			<i>Form Approved</i> OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.				
1. REPORT DATE (DD-MM-YYYY) 12-06-2010		2. REPORT TYPE Technical Information Memorandum		3. DATES COVERED (From - To) 01-11-2009 – 12-06-2010
4. TITLE AND SUBTITLE Limited Handling Qualities Evaluation of Inter-axis Control Coupling (Project Icarus)		5a. CONTRACT NUMBER		
		5b. GRANT NUMBER		
		5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Maj Dail T. Fields, USMC, Test Pilot Maj David H. Marten, USAF, Test Pilot Capt Gianmarco Di Loreto, ITAF, Test Pilot Capt Jade M. Lemery, USAF, Flight Test Engineer Capt Robert Koo, USAF, Flight Test Engineer Capt Katherine A. Ryan, Flight Test Engineer		5d. PROJECT NUMBER		
		5e. TASK NUMBER		
		5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Flight Test Center 412th Test Wing USAF Test Pilot School 220 South Wolfe Ave Edwards AFB CA 93524-6485		8. PERFORMING ORGANIZATION REPORT NUMBER AFFTC-TIM-10-03		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) USAF Test Pilot School 220 South Wolfe Ave Edwards AFB CA 93524-6485		10. SPONSOR/MONITOR'S ACRONYM(S)		
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)		
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution is unlimited; approved for public release.				
13. SUPPLEMENTARY NOTES CA: Air Force Flight Test Center Edwards AFB CA CC: 012100 Print this document in COLOR .				
14. ABSTRACT This test report presents the results for the Limited Handling Qualities Evaluation of Inter-axis Control Coupling (Project Icarus) Test Management Project (TMP). The first objective of this TMP was to evaluate handling qualities effects of longitudinal and lateral coupling. The second objective was to evaluate the use of the ADS-33E-PRF specification (paragraph 3.4.5.4) as a potential metric for fixed-wing aircraft. The USAF Test Pilot School, Class 09B, conducted 13 sorties in the NF-16D VISTA totaling 21 hours at Edwards AFB, CA from 8 to 29 March 2010. All objectives were met.				
15. SUBJECT TERMS Cross-coupling ADS-33E-PRF Control Coupling Stick Coupling Handling Qualities Project Icarus Flight Tests Bode Plot Analysis Body Axis Coupling NF-16D VISTA (Variable Stability In-flight Simulator Test Aircraft)				
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
a. REPORT UNCLASSIFIED	b. ABSTRACT UNCLASSIFIED	c. THIS PAGE UNCLASSIFIED	SAME AS REPORT	123
				19a. NAME OF RESPONSIBLE PERSON Maj David H. Marten
				19b. TELEPHONE NUMBER (661) 277-3000

This page was intentionally left blank.

PREFACE

Sincere appreciation to Mr. Bruce Cogan, NASA Dryden technical lead engineer for coupling research, for providing technical guidance to the test team. Sincere appreciation also to Mr. Dave Mitchell, aircraft handling qualities engineer with Hoh Aeronautics who served as a primary researcher developing the *Handling Quality Demonstration Maneuvers for Fixed Wing Aircraft WL-TR-97-3100* (reference 1), for providing technical guidance to the test team through NASA Dryden.

The authors gratefully acknowledge the contributions of the Calspan Corporation team for their outstanding support, especially Mr. Jay Kemper for spending many hours with the test team in the TPS handling qualities simulator.

This page was intentionally left blank.

EXECUTIVE SUMMARY

This test report presents the results for the Limited Handling Qualities Evaluation of Inter-axis Control Coupling (Project Icarus) Test Management Project (TMP). The Project Icarus test team performed testing to research inter-axis coupled aircraft handling qualities. The Project Icarus TMP was conducted at the request of the USAF Test Pilot School (TPS) in collaboration with NASA Dryden Flight Research Center. The commandant of the USAF TPS directed this program. All testing was accomplished under TPS Job Order Number MT09B100 and was conducted at Edwards AFB, CA from 8 to 29 March 2010 by the USAF TPS.

Aircraft structural and flight control surface failures alter the overall aerodynamic performance of an aircraft, degrading handling qualities to such a degree that loss of control is an issue and in the worst case, the aircraft and crew is lost. Currently, there is limited research and guidance regarding acceptable amounts of cross-coupling and the associated handling qualities. This study was an initial look at discovering a new metric to define handling qualities requirements for coupled fixed-wing aircraft. The specific objectives of this TMP were first, to evaluate handling qualities effects of longitudinal and lateral coupling and second, to evaluate the use of the *Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft* ADS-33E-PRF (reference 2, figure 12, paragraph 3.4.5.4) specification as a potential metric for fixed-wing aircraft. The long-term objective fueling this research was to provide future flight control system designers with a metric of how much coupling must be compensated for by the system to remain inside an acceptable handling qualities envelope. The ultimate goal is to improve safety of flight by increasing the ability of an aircraft to adapt to control surface impairment or damage.

All objectives were met. The test team conducted 13 sorties in the NF-16D Variable Stability In-flight Simulator Test Aircraft (VISTA) to evaluate the handling qualities effects of the aforementioned coupling on a fighter-type, fixed-wing aircraft at 15,000 feet pressure altitude and 300 knots calibrated airspeed. The study began from a limited evaluation of the ADS-33E-PRF specification (paragraph 3.4.5.4), which addresses control coupling on a rotorcraft. To accomplish the evaluation, SIMULINK[®] models were developed to represent two scenarios: first, cross-axis coupling dependent on pilot inputs and control surface deflections (stick coupling) and second, cross-axis coupling based on pitch and roll rates developed by the asymmetric (i.e. impaired) aircraft (rate coupling). Additionally, to address potential flight control system response to such cases, signal filtering was implemented in the models. On the VISTA, the project pilots flew a pitch and roll tracking task for 57 coupled configurations. Cooper-Harper ratings (CHR), pilot comments, and task performance were collected to define possible regions of similar handling qualities (level I, II and III).

The CHR results were successfully plotted (appendix F) using the ADS-33E-PRF specification (paragraph 3.4.5.4) data reduction method. Comparisons were made to the ADS-33E-PRF specification (paragraph 3.4.5.4) for rotorcraft and as expected, handling qualities levels were different but overall trends were comparable. Additionally, analysis of the CHR data showed that the CHRs correlated to coupling values in a predictable manner for stick and rate coupling. Results showed statistically relevant correlation between task performance scores and subsequent pilot ratings. Overall, the test team was successfully able to quantify the amount of cross-axis coupling and to assign a CHR for the specified task in the NF-16D VISTA.

This page was intentionally left blank.

TABLE OF CONTENTS

REPORT DOCUMENTATION PAGE.....	iii
PREFACE.....	v
EXECUTIVE SUMMARY	vii
TABLE OF CONTENTS.....	ix
LIST OF ILLUSTRATIONS.....	xi
LIST OF TABLES.....	xiii
INTRODUCTION	1
General.....	1
Background.....	1
Program Chronology.....	3
Test Item Description.....	3
Research Software	3
Research Vehicle.....	4
Test Objectives	5
TEST AND EVALUATION	7
Ground Simulation.....	7
Ground Checkout.....	8
Flying Qualities Characterization	10
Handling Qualities Characterization.....	14
Evaluation of the Use of the ADS-33E-PRF Specification (paragraph 3.4.5.4) as a Potential Metric for Fixed-Wing Aircraft	23
REFERENCES	25
APPENDIX A: COMPLETED TEST CONFIGURATION MATRIX.....	A-1
APPENDIX B: CONFIGURATION GAIN MATRICES	B-1
APPENDIX C: GAIN NAME REFERENCE LIST	C-1
APPENDIX D: FLYING QUALITIES DATA	D-1
APPENDIX E: HANDLING QUALITIES DATA	E-1
APPENDIX F: FULL PAGE PLOTS.....	F-1
APPENDIX G: FLIGHT LOGS	G-1
APPENDIX H: PILOT EXPERIENCE	H-1
APPENDIX I: FLYING QUALITIES FLIGHT SUMMARIES.....	I-1
APPENDIX J: ICARUS SOFTWARE DIAGRAMS	J-1

APPENDIX K: CONFIGURATION 000 DESCRIPTION	K-1
APPENDIX L: SIGNAL FILTERING	L-1
APPENDIX M: DATA ANALYSIS PROCEDURES	M-1
APPENDIX N: GROUND SIMULATION	N-1
APPENDIX O: PITCH AND ROLL DISCRETE TRACKING TASK	O-1
APPENDIX P: LESSONS LEARNED	P-1
APPENDIX Q: DATA PACKAGE DESCRIPTION	Q-1
APPENDIX R: COOPER-HARPER RATING SCALE	R-1
APPENDIX S: PIO RATING SCALES	S-1
APPENDIX T: LIST OF ACRONYMS AND SYMBOLS	T-1
APPENDIX U: DISTRIBUTION LIST	U-1

LIST OF ILLUSTRATIONS

Figure 1. ADS-33E-PRF Handling Qualities Specification (paragraph 3.4.5.4).....	2
Figure 2. NF-16D VISTA	5
Figure 3. Stick Coupling (dB) – Sim and Flight Data	11
Figure 4. Rate Coupling (dB) – Sim and Flight Data	13
Figure 5. Stick and Rate Coupling (dB) – Flight Data with CHR Levels	16
Figure 6. Stick Filters and Bias (dB) – Sim and Flight Data with CHR Levels	18
Figure 7. Mean Primary Task Performance with Confidence Intervals	20
Figure 8. Mean Secondary Task Performance with Confidence Intervals	21
Figure 9. Comparison to ADS-33E-PRF Specification (paragraph 3.4.5.4)	23
Figure F-1: Stick and Rate Coupling (dB) – Flight Data.....	F-1
Figure F-2: Stick and Rate Coupling (dB) – Flight Data with CHR Levels.....	F-2
Figure F-3: Stick and Rate Coupling (linear) – Flight Data with CHR Levels.....	F-3
Figure F-4: Stick and Rate Coupling (linear proportional) – Flight Data with CHR Levels.....	F-4
Figure F-5: Stick Coupling (dB) – Sim and Flight Data.....	F-5
Figure F-6: Stick Coupling (linear) – Sim and Flight Data.....	F-6
Figure F-7: Rate Coupling (dB) – Sim and Flight Data.....	F-7
Figure F-8: Rate Coupling (linear) – Sim and Flight Data.....	F-8
Figure F-9: Stick Filters and Bias (dB) – Sim and Flight Data with CHR Levels.....	F-9
Figure F-10: Stick Filters and Bias (linear) – Sim and Flight Data.....	F-10
Figure F-11: Rate Filters and Bias (dB) – Sim and Flight Data with CHR Levels.....	F-11
Figure F-12: Rate Filters and Bias (linear) – Sim and Flight Data.....	F-12
Figure F-13: Baseline Pitch Axis Bode Plot.....	F-13
Figure F-14: Baseline Roll Axis Bode Plot.....	F-14
Figure J-1. Top-Level Icarus Software on Simulator.....	J-1
Figure J-2. Icarus Stick Coupling Block.....	J-2
Figure J-3. Icarus Rate Coupling Block.....	J-3
Figure L-1. Stick Filters and Bias (dB) – Sim and Flight Data with CHR Levels.....	L-4
Figure M-1. Baseline Pitch Axis Bode Plot.....	M-2
Figure M-2. Baseline Roll Axis Bode Plot.....	M-3
Figure M-3. Baseline Configuration on ADS-33E-PRF	M-4

Figure M-4a. Various Configurations on ADS-33E-PRF.....	M-5
Figure M-4b. Various Configurations on Linear Scale Chart.....	M-5
Figure M-5. Example of Level I Primary and Secondary Task Performance.....	M-6
Figure M-6. Example of Level II Primary and Secondary Task Performance.....	M-7
Figure M-7. Example of Level III Primary and Secondary Task Performance.....	M-8
Figure N-1. Predicted Regions of Cooper-Harper Levels (Stick).....	N-3
Figure N-2. Predicted Regions of Cooper-Harper Levels (Rate).....	N-4
Figure R-1. Cooper-Harper Rating Scale.....	R-1
Figure S-1. Basic PIOR Scale.....	S-1
Figure S-2: MIL-STD-1797B PIOR Scale.....	S-1

LIST OF TABLES

Table A-1: Completed Test Configuration Matrix	A-1
Table B-1: Stick and Rate Coupling Configuration Gain Matrix.....	B-1
Table B-2: Stick and Rate Filter Coupling and Bias Configuration Gain Matrix.....	B-2
Table C-1: Stick Coupling Gains.....	C-1
Table D-1: Flying Qualities Data.....	D-1
Table E-1: Handling Qualities Data.....	E-1
Table G-1. Summary of Flights.....	G-1
Table G-2. Flight Log of Configurations Flown.....	G-2
Table H-1. Pilot Experience.....	H-1

This page was intentionally left blank.

INTRODUCTION

General

This TMP conducted a limited handling qualities evaluation of inter-axis coupling. The first objective was to evaluate handling qualities effects of asymmetric control coupling by characterizing the open-loop axis-coupled aircraft response and by collecting CHRs and pilot comments using the Pitch and Roll Discrete Tracking Task (appendix O). A second objective was to evaluate the use of the rotorcraft ADS-33E-PRF handling qualities specification (paragraph 3.4.5.4) for fixed-wing aircraft. The term open-loop refers to the aircraft response without pilot interaction, while closed-loop refers to the response of the aircraft plus the pilot.

The Project Icarus TMP was conducted at the request of the USAF TPS in collaboration with NASA Dryden Flight Research Center. The commandant of the USAF TPS directed the program. All testing was accomplished under TPS Job Order Number MT09B100. The project consisted of 13 test missions totaling 21 flight hours from 8 to 29 March 2010 using the NF-16D VISTA.

Background

Longitudinal motion of fixed-wing aircraft is typically uncoupled from lateral motion due to aircraft aerodynamic symmetry. Structural damage will negate this symmetric effect, enabling longitudinal and lateral motion to couple, which presents controllability and task performance challenges for the pilot and the flight control system (reference 3). Additionally, aircraft system failures (hydraulic, electric, etc.) can cause a similar coupled interaction through flight control surface loss. Although the motion associated with a damaged aircraft could exhibit coupling in all three axes, this test focused exclusively on lateral and longitudinal interaction.

Currently, adaptive flight control software has been implemented in multiple modeling and simulation studies and shows strong potential as a solution for failure-induced coupling (i.e. asymmetric response). Adaptive flight control systems employ neural network theory to modify flight control response to off-nominal aircraft dynamics induced by structural damage. A recent study, *Dynamics and Adaptive Control for Stability Recovery of Damaged Asymmetric Aircraft*, conducted at NASA Ames, investigated stability recovery methods using adaptive control techniques to regain stability of an asymmetric transport category aircraft (reference 3). Initial simulation described in reference 3 suggested that adaptive control using neural networks can recover aircraft stability. Implementation and flight certification continue to pose significant challenges, inhibiting their fielding.

Guidance specifications such as MIL-STD-1797B (reference 4) provide only limited direction with respect to aircraft cross-coupling since asymmetric response traditionally only occurs via off-nominal conditions and any objectionable handling qualities are generally minimized during the design and testing process. While aircraft modes of motion can be longitudinally and laterally independent, such is not the case for rotary wing vehicles. Most notably, highly agile attack and scout helicopters employ a rigid rotor system and large hinge offset in order to produce rapid response rates; however these rotor systems result in a highly coupled flight control system (reference 5). The US Army Aviation and Troop Command therefore developed a specification within *ADS-33E-PRF Aeronautical Design Standard Performance Specification Handling*

Qualities Requirements for Military Rotorcraft in order to characterize the pitch due to roll and roll due to pitch coupled handling qualities of rotorcraft (reference 2). Figure 1 below is figure 12 from the ADS-33E-PRF (reference 2, page 81), which depicts the requirement described in paragraph 3.4.5.4 of reference 2. The figure shows the pitch due to roll and roll due to pitch requirements for Cooper-Harper level I, II, and III coupled handling qualities: “The average q/p and average p/q are derived from ratios of pitch and roll frequency responses. Specifically, average q/p is defined as the magnitude of the pitch due to roll control input (q/δ_{as}) divided by the roll due to roll control input (p/δ_{as}) which is then averaged between the bandwidth and the neutral-stability (phase = -180 degrees) frequencies of the pitch due to pitch control inputs (q/δ_{es}). Similarly, average p/q is defined as the magnitude of roll due to pitch control input (p/δ_{es}) divided by the pitch due to pitch control input (q/δ_{es}) between the roll-axis bandwidth and neutral stability frequencies (ϕ/δ_{as})” (reference 2). Throughout this report, figure 1 is referred to as the ADS-33E-PRF specification (paragraph 3.4.5.4).

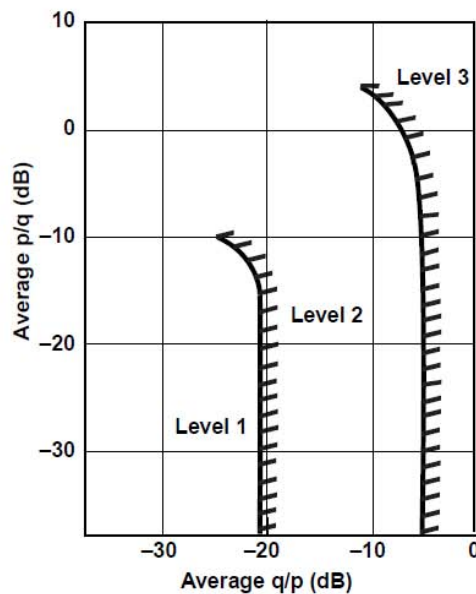


Figure 1. ADS-33E-PRF Handling Qualities Specification (paragraph 3.4.5.4)

The ADS-33E-PRF handling qualities specification (paragraph 3.4.5.4) has served as a starting point for initial fixed-wing coupling research being conducted at NASA Dryden Flight Research Center. Initial Dryden studies involved using a cross-coupled SIMULINK[®] model in the F/A-18 flight test simulator in order to develop a methodology to evaluate coupled aircraft handling qualities. The customer for this TMP requested the team to evaluate the potential for the ADS-33E-PRF specification (paragraph 3.4.5.4) to provide criteria to delineate between handling qualities levels for fixed-wing aircraft.

NASA Dryden’s technical lead engineer for coupling research provided technical guidance during this test project. Additionally, an aircraft handling qualities engineer with Hoh Aeronautics provided engineering and research support for this test project through NASA Dryden. This engineer served as a primary researcher developing the *Handling Quality Demonstration Maneuvers for Fixed Wing Aircraft WL-TR-97-3100* (reference 1). Specifically, the Discrete Pitch and Roll Tracking Task from WL-TR-97-3100 was used as the tracking task to

evaluate the coupled handling qualities of the test configurations. A complete description of the tracking task is located in appendix O.

This TMP used a SIMULINK[®] model to simulate inter-axis stick and rate coupling in the TPS handling qualities simulator and in-flight in the NF-16D VISTA, with the purpose of evaluating cross-coupled aircraft handling qualities.

Program Chronology

A configuration control board meeting was held on 1 February 2010 to review and baseline the Icarus software. A joint technical review board (TRB) and safety review board (SRB) was conducted on 8 February 2010. The TRB was chaired by Mr. David Vanhoy, USAF TPS/CT. The SRB was chaired by Mr. Justin Chulyak of AFFTC/SET.

The test project consisted first of 48 hours of simulator flights in the TPS handling qualities simulator from 1 to 26 February 2010. Next, 20 hours of ground checkout were accomplished on the VISTA from 1 to 8 March 2010 using VISTA's ground simulation mode. Finally, 13 test flights (21.0 hours) were flown in the VISTA from 8 to 29 March 2010.

Test Item Description

Calspan Corporation provided contractual support to the Project Icarus to design the flight software for the NF-16D VISTA as specified by the test team. VISTA configuration 000 (see appendix K), which consisted of the F-16 bare-airframe dynamics augmented in the pitch axis for stabilization purposes (reference 6), was used to ensure safety limits were in place, and served as the base for test configurations. The Icarus software, which consisted of a SIMULINK[®] model to enabled coupling of longitudinal and lateral loops, was implemented on configuration 000 to create the baseline (configuration 801) for test configurations.

Research Software

The Icarus software simulated coupled aircraft responses through coupled stick control loops, coupled pitch and roll rate loops, and signal time delay, bias and filtering. Two modules were implemented in the model: stick coupling and rate coupling.

The stick coupling module (figure J-2) modified pitch and roll stick commands to the VISTA flight control system through variation of gains. To cause pitch coupling due to roll inputs, a portion of the pilot-input roll command was injected into the pitch stick command path via a direct gain. To cause roll coupling due to pitch inputs, a portion of the pilot-input pitch command was injected into the roll stick command. These gains were changed to vary the amount of cross-coupling to be induced. Variation of coupling as described here is referred to as single-axis coupling, since only one command path is being altered at a time. Additionally, two-axis coupling was also induced using this module. This was done by varying both loop gains at the same time. The stick coupling block was configured to add a time delay and an angular rotation of the stick input, capabilities which were not used during this test. Also, a bias gain was designed to create a constant input which would then be consistently present in the command path, regardless of stick actuation. The concept was to simulate an asymmetry which could not

be compensated for via the standard trim system. Another feature programmed in the software and used extensively in flight was the filtering of the inputs. Two filters were implemented to simulate an incomplete control system compensation for an impaired surface, or to simulate the control system overdriving another surface to compensate for the impaired one. Specifics about their programming and implementation are in appendix L.

The second module, rate coupling (figure J-3), was similar to the first except that the coupling was accomplished at the pitch acceleration and roll acceleration command paths versus the stick command paths. The objective was to simulate a coupled response generated by an asymmetric structure reacting to a lift vector change (i.e. positive/negative pitch and roll rates). To accomplish pitch due to roll coupling, a portion of the roll rate was injected into the pitch acceleration command path, whereas for roll due to pitch coupling, another gain was used to inject pitch rate from the longitudinal feedback loop into the roll rate command forward loop. This was again referred to as single-axis coupling. Two-axis coupling was accomplished by varying both of these gains. Delay, bias, and filtering were accomplished as described above for the stick coupling module.

The Icarus software model was developed and executed using SIMULINK[®] on a desktop computer in order to initially characterize roll due to pitch and pitch due to roll coupled responses to programmable test inputs (PTI). Concurrently, the software was incorporated into the TPS handling qualities simulator to both validate desktop results as well as refine the test matrix prior to flight. Once software simulator testing was complete, the Icarus software was then loaded into the VISTA aircraft which enabled in-flight handling qualities testing of the cross-coupled configurations. Appendix J shows the Icarus software modules (figures J-2 and J-3) and the model displaying where they were integrated into the simulator control paths (figure J-1).

Research Vehicle

The VISTA (figure 2) was a highly modified Peace Marble II Block 30 F-16D with Block 40 avionics. It was capable of high fidelity simulation of “model” aircraft characteristics in the real flight environment. Airframe modifications included a large dorsal, heavy duty landing gear, programmable head-up-display (HUD), variable feel system for center stick, and high performance control surface actuators. The VISTA Simulation System (VSS) used five control surfaces and the engine to mimic the feel and response of the simulated aircraft. The VSS could be modified with different control architectures such as the flight control software developed by this test project to enable the inter-axis control coupling to be evaluated. The VSS also contained a complete aircraft model that enabled the aircraft to be “flown” on the ground. The system evaluation pilot occupied the front cockpit and the safety pilot occupied the rear cockpit. In the VSS mode, PTIs could be initiated by either cockpit to evaluate the dynamic response of the aircraft and/or controller performance.



Figure 2. NF-16D VISTA

The Digital Flight Control Computer (DFLCC) continually monitored pilot inputs for safety. If the VSS commands to the control surface actuators approached basic aircraft limits, the DFLCC would disengage the VSS and revert to the basic F-16 control mode. The VSS also included dual sensors for all required signals and a sensor failure would cause an automatic safety trip. Either pilot could initiate a manual safety trip as well. Following a safety trip, aircraft control instantly returned to the safety pilot occupying the rear cockpit.

Test Objectives

The first objective of this TMP was to evaluate handling qualities effects of longitudinal and lateral coupling. The second objective was to evaluate the use of the ADS-33E-PRF specification (paragraph 3.4.5.4) as a potential metric for fixed-wing aircraft. This was accomplished by characterizing the open-loop, coupled aircraft response and by collecting Cooper-Harper ratings and pilot comments using the Pitch and Roll Discrete Tracking Task. All objectives were met.

This page was intentionally left blank.

TEST AND EVALUATION

The first objective of this TMP was to evaluate handling qualities effects of longitudinal and lateral coupling. The second objective was to evaluate the use of the ADS-33E-PRF specification (paragraph 3.4.5.4) as a potential metric for fixed-wing aircraft. The test aircraft was the NF-16D VISTA, operated by Calspan. In support of the project, Calspan implemented the cross-coupling models in the VSS flight control computers utilized on the VISTA. Ground simulation events using the TPS handling qualities simulator and ground test on the VISTA were completed prior to flight test. Forty-eight hours of ground simulation were completed from 1 to 26 February 2010, and 20 hours of ground checkout in the VISTA were completed from 1 to 8 March 2010. The simulation events were used to: develop the test matrix, validate the cross-coupling software, establish consistent data collection procedures, develop the data reduction scripts and gain familiarity with the primary and secondary task. The ground checkout events on the VISTA were used to: verify correct configuration gains, verify primary and secondary task operation, shape the frequency sweeps (determine frequency range for PTIs to avoid encountering the aircraft's safety trip limits during the sweep), determine set-up attitudes for initiation of the PTIs (attempting to keep the aircraft straight and level through the sweep as much as possible), validate the data reduction process, and gain familiarization with the in-aircraft procedures.

Flight tests were flown from 8 to 29 March 2010 and consisted of 13 VISTA test sorties (21.0 hours). The flight test events were divided into four flying qualities flights and nine handling qualities evaluation flights. All flights were flown within the R-2508 complex at Edwards AFB, California.

The flying qualities sorties were used to determine aircraft characteristics and dynamics under each tested configuration. PTI frequency sweeps were used to characterize the open-loop coupled response. Each flying qualities sortie was flown with an Icarus flight test engineer in the front cockpit and a VISTA safety pilot in the rear cockpit. The remaining nine handling qualities sorties were flown by the project pilots to evaluate the handling qualities effects under multiple control coupling configurations. The primary implementations of interest were stick and rate coupling in both the longitudinal and lateral axes. Additional test points included stick and rate coupling with a second order washout filter applied (appendix L), and control bias cross-coupling configurations. The test team completed a pitch and roll tracking task and collected CHR, pilot in the loop oscillation (PIO) rating (PIOR), and pilot comments for each cross-coupled configuration. A secondary task was completed during each maneuver; however the results of the task were available for post-flight analysis but not in-flight review. Data were collected during each of the 13 test sorties.

Ground Simulation

Procedure

The ground simulation events were used primarily to develop the test matrix. This was accomplished by the engineers selecting numerous cross-coupling gain values for the pilots to fly in the simulator. The gains were varied to determine at what values the pilots encountered level

I, II, and III handling qualities for each type of coupling implementation (stick, rate, filters, and bias). For each coupled scenario, the pilots assigned a CHR and PIOR and provided comments related to the handling qualities.

Results and Analysis

More than 230 scenarios were flown during ground simulation using the procedure described above. The CHRs associated with these scenarios were compared to determine approximate level I, II, and III regions as shown on figures N-1 and N-2 in appendix N. The test matrix configurations were then created to achieve a relatively even dispersion of gain values across the regions for stick and rate coupling. There were three axes of interest: pure pitch due to roll (q/p, or x-axis points); pure roll due to pitch (p/q, or y-axis); simultaneous q/p and p/q with equal gains (45 degree line on the ADS-33E-PRF, paragraph 3.4.5.4, chart). Twenty primary stick coupling configurations, plus nine backup stick coupling configurations were created. The primary configurations were those intended to be evaluated during the flight tests. The backup configurations were created to allow flexibility to either fly additional configurations if able or shift the primary point's gain value based on flight results without requiring reprogramming of the configuration. Nine primary rate coupling configurations plus 21 back up rate coupling configurations were created. The filter configurations were selected by choosing predicted level II stick and rate coupling points as the basis. Four primary and four backup stick filter configurations were created, each being evaluated for two filter types (16 total points). Two primary and two backup rate filter configurations were also created, each being evaluated for the same filter types (eight total points). The bias configurations were selected to give a signal input of 25 percent and 50 percent, based on 100 percent representing the maximum available stick input or rate input as appropriate to the model and axis affected. Two primary and two backup bias configurations for each of stick and rate coupling were created (eight total points). Only the predicted Cooper-Harper level regions (determined from the simulation) were considered during selection of the configurations, not where these configurations would fall on the ADS-33E-PRF (paragraph 3.4.5.4) format chart. The test matrix (appendix B) was comprised of a total of 92 configurations. For more information on the development of the test matrix and the results of the ground simulation events, see appendix N.

Ground Checkout

Procedure

Ground checkout was completed prior to test flights in order to verify and validate the SIMULINK[®] model tested in the simulator. System operation was checked by applying ground power to the VSS and engaging each configuration in the test matrix. Cross-coupling gain values were confirmed and PTI entry and operation was tested for each configuration. The primary and secondary task operation was verified in multiple configurations. The process of verification was utilized to fine tune the test matrix prior to flight tests. All VSS data were recorded and analyzed in order to refine data reduction procedures and verify simulator open-loop data for each configuration.

Results and Analysis

The cross-coupling configurations were loaded and verified for gain values without issue. When the PTIs for pitch frequency sweep and roll frequency sweeps were executed in the VSS ground simulation mode, unexpected safety trips occurred (mainly rate limiting on the stabilators). During the development of the test matrix, a wide range of cross-coupling configurations were modeled in SIMULINK[®] and run in the flying qualities simulator. The implementation of the VISTA safety trips though, was only partial at the time of the simulation phase (only the angle-of-attack and vertical acceleration (N_z) limits were coded). As a result, the ground checkout revealed a tendency to command the horizontal stabilators beyond the acceptable 70 degrees per second limit during the high frequency portion of the sweeps. The PTI frequency range had to be reduced to 0.2 to 12 radians per second with a power of one (in SIMULINK[®] the power represents the dwell time at each frequency; with power equal to one, the 30 seconds of the sweep were equally divided within the frequency range) to remain within the VSS limits. The reduced range (i.e. frequency bandwidth) of the PTIs increased the technical risk of not fully characterizing the open-loop dynamics of each configuration.

Primary task operation in the VSS ground mode provided the opportunity to verify HUD symbology and gain experience operating the center stick of the VISTA. The HUD symbology included the flight path marker (FPM) and horizon line. The FPM and horizon line were not present in the simulator during VSS operation and it was assessed that the extra symbology added clutter and did not significantly increase situational awareness. Additionally, the actual feel of the center stick in VISTA was noticeably different than the simulator. The center stick was much shorter in the aircraft than in the handling qualities simulator and resulted in smaller control deflections, and the feedback provided by the VISTA resulted in less stick force per g. The secondary task was verified for symbology.

Configuration PTIs, primary task, and secondary task data were recorded by the VISTA mission computers and transferred to external drive to aid with data reduction script development. PTI data reduction revealed a need for minor modifications in reduction script, and the secondary task data reduction produced a need to create an entirely new script. The differences in data output between the TPS handling qualities simulator and VISTA VSS added to data reduction time, but were helpful in analysis by executing primary task playback in the TPS handling qualities simulator based on aircraft data.

Flying Qualities Characterization

Procedure

Open-loop techniques, including frequency sweeps, impulses, steps, and doublets were employed to collect data for flying qualities characterization of cross-coupled test point configurations. A total of four flying qualities test flights were flown to collect open-loop flying qualities data for the baseline configuration and the cross-coupled configurations. Pitch and roll PTI frequency sweeps were performed to produce Bode plots to identify phase and gain margins (see figures F-13 and F-14 for the baseline configuration). Limited open-loop flight test techniques (raps and doublets) were completed in an effort to further characterize the flying qualities of the baseline configuration (801).

Flying qualities test flight procedures were as follows: the safety pilot stabilized the aircraft at 15,000 feet pressure altitude (PA), 1g, and 300 knots calibrated airspeed (KCAS). The pitch and roll PTI frequency sweeps were completed from 0.2 to 22 radians per second for the baseline configuration and 0.2 to 12 radians per second for cross-coupled configurations. Each PTI was programmed for a 30 second time period with an equal dwell time at each frequency.

Results and Analysis

A list of completed test configurations and the resultant q/p and p/q values (simulated and in-flight) can be found in appendix A and D, respectively. Also, a summary of each flight and the corresponding list of configurations flown are included in appendix G, whereas the results of each flying qualities flight are included in appendix I. Following is a detailed analysis of the findings.

VISTA Baseline Characteristics (Configuration 801)

The first task of the flying qualities investigation was to characterize the VISTA baseline configuration in the VSS mode. Test configuration 801 consisted of the Icarus software model hosted in the VSS computers with cross-coupling gains set to zero. Any actual coupling occurring using configuration 801 would have been a result of any inherent bare-airframe coupling present on the NF-16D aircraft. Open-loop flight test data were collected using pitch and roll PTI frequency sweeps and manual sweeps, steps, and trim shots.

Configuration 801 exhibited a roll due to pitch (p/q, on vertical axis) coupling at nearly a 1:1 ratio. This was evident in that a pitch step to 30 degrees nose-up resulted in a 30 degrees right roll and vice-versa. The VSS lateral stick gain values were then set to zero, in an attempt to eliminate any lateral stick input by the pilot, and the same right roll developed during any pitch-up steps, while a left roll developed during any pitch-down steps. Analyzing the data to determine average baseline coupling (see appendix M for data analysis procedures) showed that the inherent coupling observed in the VISTA significantly shifted the baseline configuration as compared to simulation data (see figure 3). Also, after further investigation into the VSS software architecture, it was determined that the baseline VSS model (configuration 000), used to interface with the Icarus software models, did not have a lateral feedback loop. As a result, any inherent coupling in the roll axis was not damped nor stabilized by the flight control system when in VSS mode.

Figure 3 below shows the SIMULINK[®] open-loop data for stick coupling test configurations compared to the flight test results. Baseline simulation data predicted a roll due to pitch (p/q) coupling value of -325 dB (point inside the square) whereas flight test data showed a p/q of -7.7 dB (point inside the circle). Looking at the opposite axis, pitch due to roll (q/p), a minor shift of approximately 10 dB was evident between simulation and flight test data. While the NF-16D's inherent coupling (p/q) was measured and analyzed, a conclusive cause could not be determined within the scope of this test; more information on what was done to investigate this coupling can be found in appendix P. Note that this inherent roll coupling was therefore a component of all coupled configurations. Although the baseline configuration exhibited more coupling than anticipated, there was no impact on test results or conclusions; coupled handling qualities were evaluated based on the measured values.

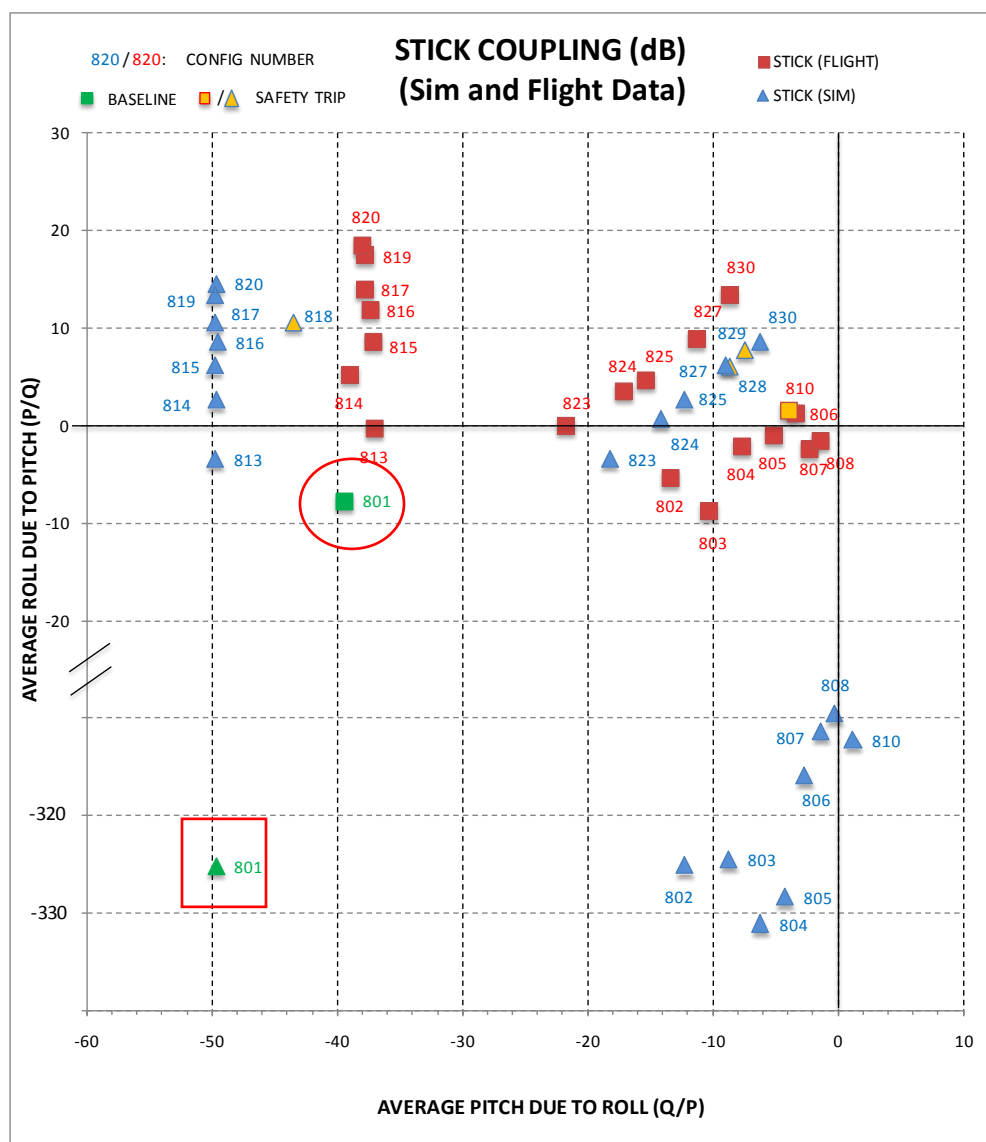


Figure 3. Stick Coupling (dB) – Sim and Flight Data

Stick Coupling Configurations (802-830)

Frequency sweeps were completed for most stick coupling test configurations with sufficient data being collected to generate Bode plots of pitch rate due to roll rate (q/p) and roll rate due to pitch rate (p/q). Frequency sweeps were not completed in flight for configurations 818, 828, and 829 due to either exceeding VSS control surface rate command limits when attempted, or the point was not attempted due to anticipated exceedence of VSS limits based on build-up configurations. Configuration 810 encountered a safety trip during the sweeps, but sufficient data was collected to plot the point. For the simulation data, configurations 818, 828, and 829 encountered trips during the SIMULINK[®] model frequency sweep as well. Figure 3 above shows the resultant plots of average p/q and q/p for flight and simulation data. Test configurations 802-810 exhibited a roll due to pitch (p/q) shift corresponding to the baseline shift as previously discussed. Also, pitch due to roll (q/p) showed less aircraft pitch response than the simulator, with the flight test points falling to the left of the simulation data. Configurations 813-820 exhibited a 10 dB difference in q/p between simulation and flight data. Two-axis coupling (q/p and p/q ; configurations 823-830) data were more consistent with simulation data.

Rate Coupling Configurations (832-859)

Nine rate coupling configurations were evaluated, consisting of three roll due to pitch (843, 848, 853), three pitch due to roll (832, 836, 840), and three two-axis coupled configurations (854, 856, 859). Average coupling values for simulation and flight data are plotted in figure 4. The flight test rate coupling data showed a similar shift pattern in both axes as the stick coupling configurations. Frequency sweeps were not completed in flight for configurations 840, 856, and 859 for the same reasons listed for stick coupling. As a result, the three points are not plotted on the chart. Configuration 853 encountered a safety trip during the sweeps, but sufficient data were collected to plot the point. The rate coupling gain values chosen corresponded to gain values used to generate the stick coupling configuration. Average coupled rates (q/p and p/q) for a given gain setting were similar whether the coupling was generated using stick or rate command loops.

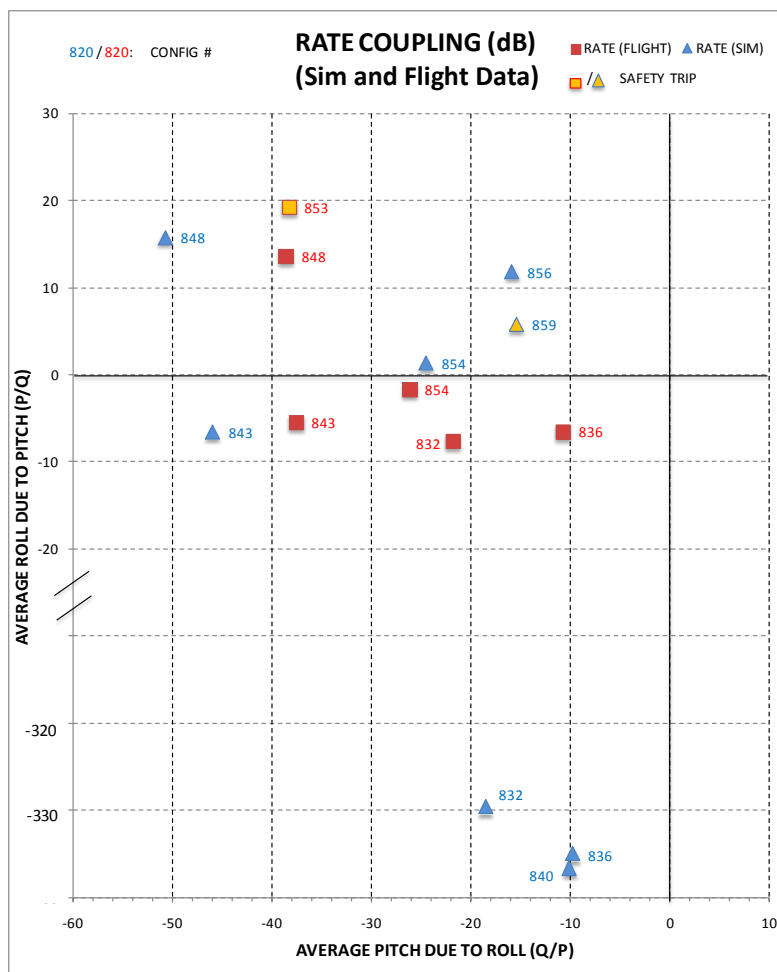


Figure 4. Rate Coupling (dB) – Sim and Flight Data

Stick and Rate Coupling with Filters Configurations (860-884)

Twenty filter test points were evaluated consisting of 14 filters on stick-coupled configurations and six filters on rate-coupled configurations. Average coupling values for simulation and flight data are plotted in figures F-9 through F-12. Frequency sweeps were not completed in flight for configurations 867, 868, 873, 882, 883, and 884 for the same reasons as described for stick coupling. Configuration 866 encountered a safety trip during the sweeps, but sufficient data were collected to plot the point. Specifics of the effects of filters are in the following handling qualities section and in appendix L.

Bias Configurations (885-892)

Four bias configurations were evaluated consisting of two bias configurations using the stick coupling model and two bias configurations using the rate coupling model. Average coupling values for simulation and in-flight data are plotted in figures F-9 through F-12. Frequency sweeps were not attempted in flight for the bias configurations 886, 888, 890, and 892 due to the expected dynamics: the bias would cause the frequency sweep to be off-trim and quickly encounter a safety trip.

Handling Qualities Characterization

A total of nine handling qualities test flights were completed to collect CHRs and PIORs for each configuration. Each of the three pilots on the test team completed three handling qualities flights. Each pilot had a different operational background (see appendix H).

Procedure

With the intent of capturing ratings from each pilot on all primary points of the test matrix, the handling qualities flights were organized into three segments (stick, rate, and filter effects) and flown by all three pilots. Each pilot evaluated most of the cross-coupling configurations selected from the test matrix, presented in a random order. In order to avoid a build-up which could have generated expectations and biased pilot comments, the type and order of the cross-coupling configurations to be flown was unknown to each test team pilot. An exception was for configuration 801, which was flown and known to the pilot as the first run on each of the flights. The same configuration was re-flown during each sortie at run 12. The kneeboard cards utilized by each pilot consisted of run number and no configuration label associated with the actual cross-coupling values. However, the flight test engineer (FTE) in the control room and safety pilot retained access to the order and cross-coupling values of each test point. Each flight completed evaluation of between 17 and 25 configurations including the baseline configuration.

Test flights began with a climb to 15,000 ft PA and 300 KCAS by the safety pilot. Once on conditions for the test, the safety pilot engaged the baseline configuration and the pilot in the front cockpit engaged the center stick and matched the throttle position prior to taking control of the aircraft. Once aircraft control had been transferred to the front cockpit, the test team pilot engaged the primary task and the safety pilot started timing. The safety pilot communicated to the control room the run number and record number. The secondary task automatically engaged and ran for the duration of the primary task. The pitch and roll task programmed in VISTA and described in appendix O consisted of matching a fixed sight with pitch and roll indicators to a moving pitch and roll command line. The task ran for two minutes and 30 seconds, but was terminated after approximately two minutes (as timed by the safety pilot) when the command line assumed a level attitude.

During the task, the pilot attempted to complete a secondary task, which consisted in matching an arrow present in the upper left corner of the HUD with the cursor designator on the throttle. The arrow was programmed to change direction every three seconds. After the task was terminated, the test team pilot disengaged the primary task and recorded pitch performance from the HUD display. Pilot assessment of the CHR and PIOR, and pilot comments regarding the configuration were based on a subjective assessment of overall performance due to the lack of roll performance available real time in the cockpit; see the results and analysis section below for further details. The pilot verbally stepped through the CHR scale via VHF mission frequency to the control room. Pilot comments were recorded by the FTE in the control room, the safety pilot when able, and by audio recorder carried by the test team pilot. During the control room debrief following each test point, the instructor pilot entered the next configuration and returned the aircraft to within the data band (15,000 ft PA \pm 1000 ft, 300 KCAS \pm 25 KCAS).

Results and Analysis

Stick Coupling

A total of 24 stick coupled test configurations (23 plus baseline) were flown by three evaluation pilots resulting in three Cooper-Harper ratings at all but two of the planned 24 configurations. Configurations 818 and 830 were flown by two of the three pilots. A summary of Cooper-Harper ratings is shown in appendix E. Resulting task performance scores were significantly higher than the task-defined 50 percent criteria for desired performance. As a result, the displayed task performance score could not be used to differentiate desired versus adequate performance, and pilot ratings focused on workload and compensation, while using the HUD-displayed pitch tracking performance score as a reference. Post-flight analysis showed that a task performance pitch score of greater than approximately 70 percent within the desired region (inner circle of the gun sight) appeared to correlate to desired (level I) performance, less than 70 percent within the desired region appeared to correlate to adequate performance, and less than 80 percent within the adequate region (outer circle) appeared to correlate to not adequate performance. Overall, all three evaluation pilots noted that the in-flight tracking task was easier than the simulator due to the availability of acceleration cues (N_z).

Figure 5 shows the test configurations with the associated CHRs. Analysis of the CHR data showed that the CHRs correlated to coupling values in a predictable manner, allowing handling qualities level regions to be annotated on the chart. More specifically, increased gains corresponded to deteriorated handling qualities and consequently to higher CHRs. Since the test matrix was developed on three main axes only (q/p, p/q, and q/p plus p/q of equal magnitude), dashed hand-faired lines were used to suggest the regions outside of the tested areas. The level I, II, and III handling qualities regions on the ADS-33E-PRF (paragraph 3.4.5.4) format chart (figure 5) were drawn from limited data (i.e. the identified test matrix) and were applicable only for the VISTA at the stated test conditions and configurations, and may not transfer to other induced coupling configurations, aircraft, or flight conditions. When a test configuration showed ratings in more than one level (among the three pilots), judgment was used for placement of the region boundary. The boundary was drawn based on the two matching ratings for convenience, though all three ratings remain relevant data for the configuration.

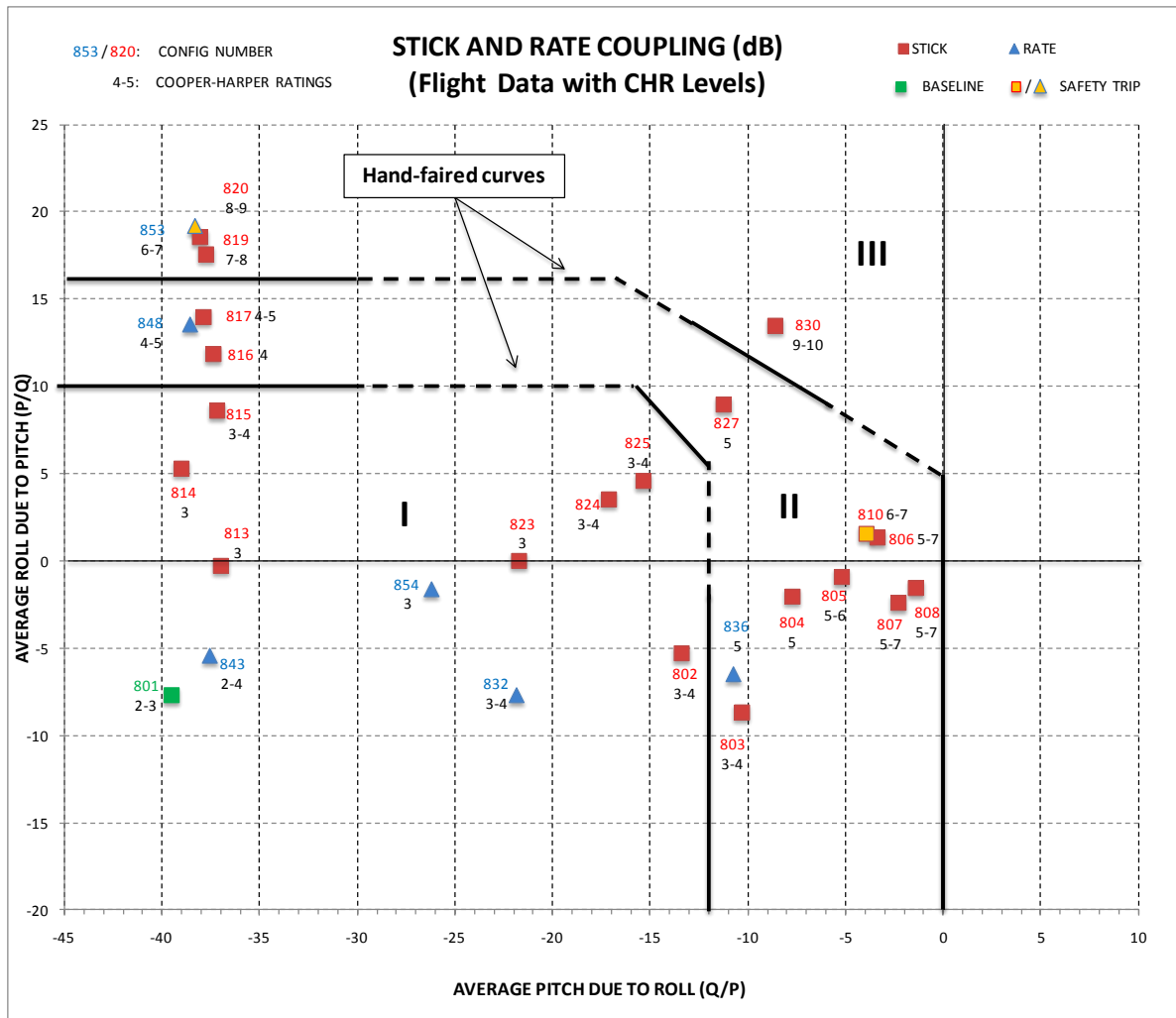


Figure 5. Stick and Rate Coupling (dB) – Flight Data with CHR Levels

During the handling qualities evaluation it was also noted that the normal g (N_z) associated with pitch rates provided immediate feedback to the pilot, which resulted in the ability to more effectively compensate for coupling-induced roll. Also, coupling-induced pitch rates were notably more uncomfortable causing the evaluation pilot to reduce gain and sacrifice tracking performance. In addition to plotting the test results in the ADS-33E-PRF specification (paragraph 3.4.5.4) format, the results were also plotted with a linear scale of average p/q and q/p instead of the original dB scale. The linear scale was a more intuitive representation of the relative magnitude of pitch due to roll and roll due to pitch coupling, since the averaged values were now directly related to the gains used in the software modules. As a result, it was noted that pilots could handle up to three times more roll due to pitch than pitch due to roll, even if VISTA was able to generate much larger roll rates than pitch rates. For example in viewing figure F-4, it can be directly understood that a pilot could tolerate more roll due to pitch than pitch due to roll as the Cooper-Harper level regions are larger in the y-axis. This conclusion was more ambiguous when viewing the results in a dB scale (figure 5). Appendix F includes multiple plots depicting the degree of cross coupling and the associated CHR for each configuration.

Rate Coupling

A total of nine rate coupling points were flown by the three evaluation pilots. The rate coupling data correlated to coupling values in a predictable manner as had the stick coupling data (i.e. increased gains equaled increased pilot ratings). CHR and PIORs were also similar for similar gains, allowing for plotting both results on the same chart (figure 5). These results suggest that resultant cross-coupled handling qualities appeared to be driven by the amount of out-of-axis coupling rather than the method of inducing the coupling (i.e. stick or rate coupling).

Three of the nine configurations (840, 856 and 859) were not included in figure 5 due to insufficient flying qualities data, as described in the flying qualities section above. Configuration 840 was pitch due to roll rate (q/p) and utilized a gain value of 2.5 and was rated level III. Configurations 856 and 859 were two-axis rate coupling with gain values of 0.75 and 1.5, and Cooper-Harper level II and III, respectively.

Configuration 853 (roll due to pitch rate, p/q) tripped during the frequency sweep not allowing a full frequency spectrum characterization, and was therefore shown in yellow to note the unreliability of the data. This configuration utilized a gain value of 2.5 and was rated level III. The CHRs and PIORs are listed in appendix E for all nine configurations.

Filter Effects

Overall, it was determined by comparing the filtered test configurations against the unfiltered configurations (see table B-2 for correlation) that the tested filters had an adverse effect on Cooper-Harper ratings. As implemented, the filters had the effect of „spiking“ the induced coupling, resulting in „jerky“ handling qualities during the tracking task. Pilot workload and compensation, as indicated by pilot comments, were increased over the unfiltered case. The ADS-33E-PRF (paragraph 3.4.5.4) method of attaining average coupling values could not completely characterize the filter-induced coupling. Figure 6 depicts the results of the filters on stick coupling configurations. The Cooper-Harper level regions shown on figure 6 are duplicated from figure 5 and were not specifically drawn with respect to the filter configuration results. Figures F-9 to F-12 show the results of the filters on stick and rate coupling configurations. See appendix L for a more detailed explanation of signal filtering.

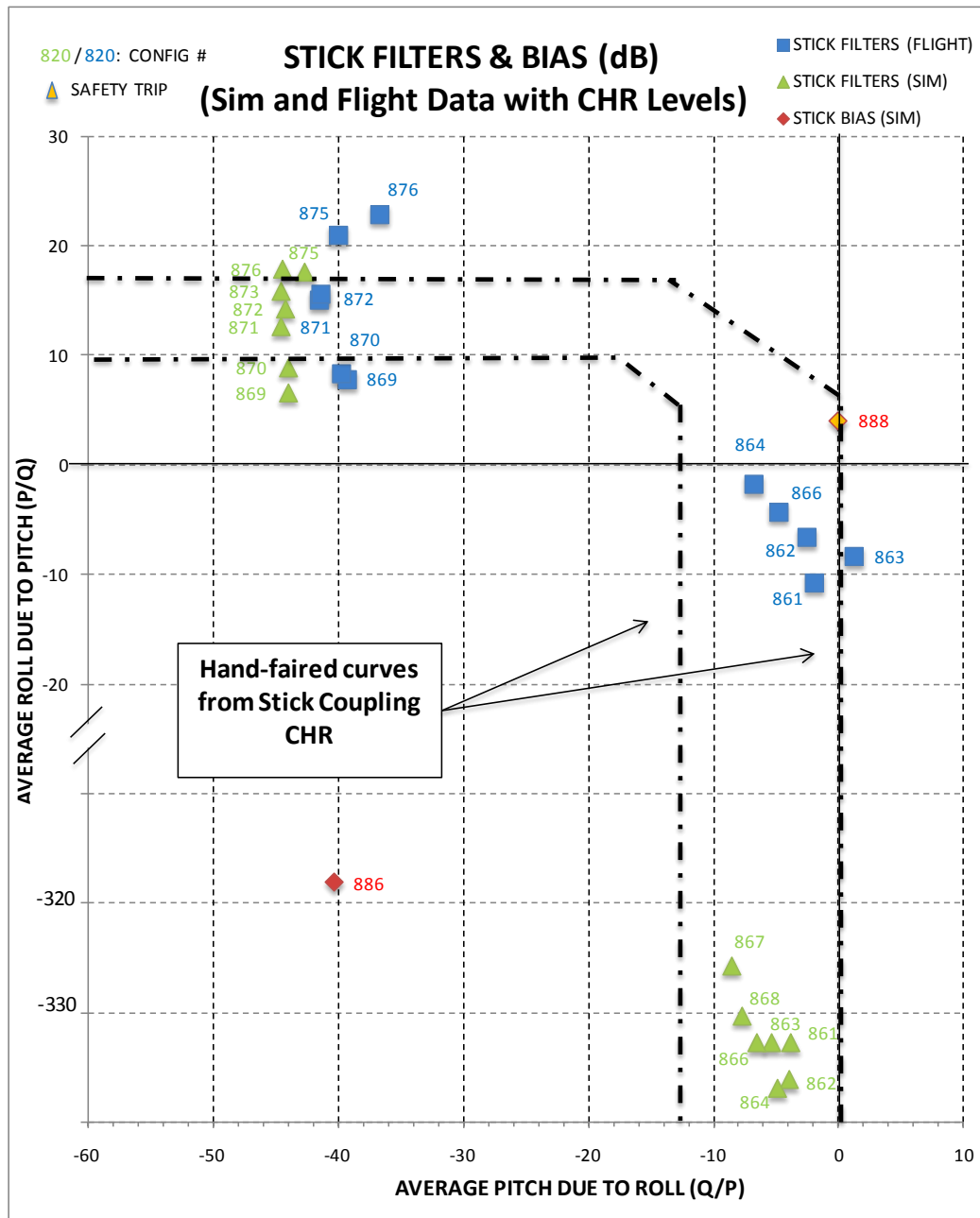


Figure 6. Stick Filters and Bias (dB) – Sim and Flight Data with CHR Levels

Bias Effects

Four configurations tested utilized stick or rate bias to generate cross-coupling, and all were flown by the three evaluation pilots. While the input was generated at the stick for control coupling and through rate feedback for rate coupling, the effect was notably similar. Each bias point behaved like an aircraft in an asymmetric trim state. Configuration 886 generated a pitch up bias, 890 was a pitch down bias, 888 was a roll left bias, and 890 a roll right bias. The task performance, CHR, PIOR, and pilot comments can be found in appendix E and reflect a trend of moderate physical workload with low mental workload. Each pilot commented that cross-

coupling was not noticeable, but constant stick pressure was required to counter the biased input. CHRs for each configuration were borderline level I and II, with two of three evaluation pilots providing CHR 3 and the remaining pilot varying between CHR 4 and 5. The PIORs ranged from 1-3 and reflected that the evaluation pilots observed undesirable motions: if the pilot did not maintain the proper stick deflection required to counter the configuration bias, then undesirable motion occurred. However, oscillations were not observed as a function of the pilot plus vehicle interaction under the biased configurations. Using stick or rate bias as a technique to generate cross-coupling was not effective under the conditions evaluated.

Primary Task Performance Analysis

The primary task used to generate CHR and PIORs for each configuration (the pitch and roll discrete tracking task described in appendix O) defined overall performance based on percentage of time the pilot maintained the fixed pipper within defined pitch and roll error limits from the command bar. Desired performance was defined as the fixed pipper being within 10 mils pitch error (inner ring) and 10 mils roll error (measured from the end of the command line) for more than 50 percent of the task duration. Adequate performance was defined as the pilot being able to maintain 20 mils pitch (outer ring) and roll (measured from the end of the command line) for more than 50 percent of the task duration. The desired and adequate scores obtained by the pilots were driven by the criteria mentioned above, but although the task made measurements in both pitch and roll, VISTA only displayed the resultant pitch error at the end of each task. Therefore, the overall (pitch plus roll) performance measurements were not available to the pilot when the CHR scale was used real time in flight. Also, it was noted that measuring the amount of time within the desired bounds only was easier for data reduction purposes and more relevant from a statistical standpoint. Consequently, actual primary task performance, as a function of the desired performance criterion only for pitch, roll, and the combination of pitch and roll associated with Cooper-Harper level I, II and III, are presented below in figure 7, with 95 percent confidence interval for the mean depicted. The results indicated that the overall pitch, roll, and the combined performance means were statistically different between the three handling qualities levels.

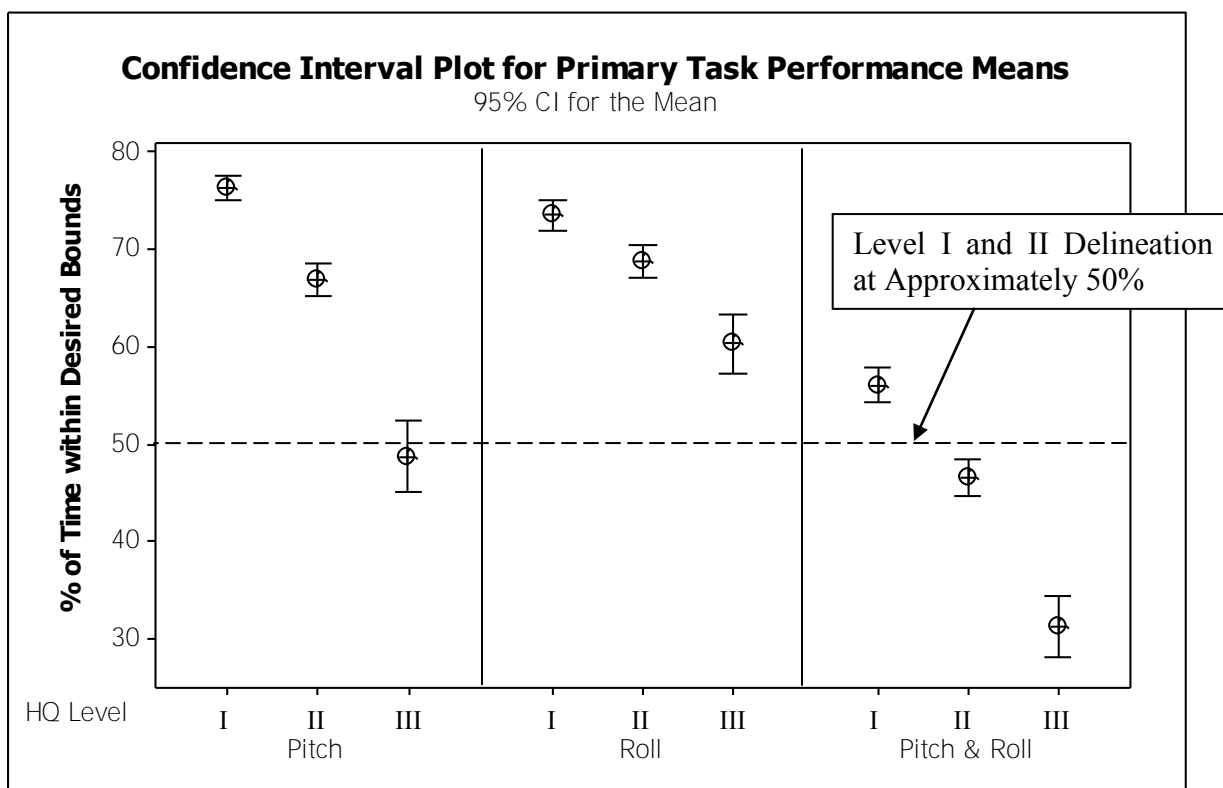


Figure 7. Mean Primary Task Performance with Confidence Intervals

Combined performance for level I configurations was 56 percent of time within the desired error bounds, and level II was 46.6 percent of time within desired error bounds. The combined pitch and roll performance provided delineation between level I and II at approximately 50 percent of time within the desired error boundaries (10 mils). Figure 7 depicts the ability to use the mean “percent of time” within desired pitch error bounds in order to assist the pilot with determination of the CHR (as previously mentioned, the pilot had no real-time, quantitative feedback of the roll performance achieved).

Pitch performance could be used to define desired performance as greater than 70 percent of the task within 10 mils error bounds, and adequate performance as greater than 50 percent of the time within 10 mil error bounds. The test flight pitch performance mean associated with level I was 76.7 percent, level II was 66.9 percent, and level III was 48.7 percent within the desired error bounds. The inability to use predefined performance parameters to delineate between desired and adequate performance did not allow the test team to use task performance as intended during the generation of CHRs. However, the CHRs collected during the test flights, using as task performance the overall assessment made in-flight by the pilots, were consistent with the desired and adequate performance measured post-flight with the techniques shown in this paragraph. As a result, all the ratings collected were deemed valid and statistically relevant. **Recommend providing the pilot with a combined pitch and roll performance score following completion of the discrete tracking task for future handling qualities evaluations. (R1)¹**

¹ Numerals following an R represent tabulated recommendation numbers.

Secondary Task Performance Analysis

The secondary task utilized was intended to reflect pilot workload and excess mental capacity available during execution of the primary task. Figure 8 below indicates that the secondary task scores between Cooper-Harper level I and II were not statistically different. However, between Cooper-Harper level I & III and II & III, differences were detected. The primary task was low g (0.3-2.0g) and was exactly the same each time. Each consecutive execution of the primary task meant that the pilot was more familiar with the task and able to complete it using less active processing. The pilot's ability to complete the primary task with excess mental capacity available was consistent with the fact that there was not a clear delineation between level I and II secondary task performance. Additionally, the association of a level III aircraft with a pilot working as hard as possible, but not achieving adequate performance or struggling to maintain control was consistent with a drop off in secondary task performance. In all cases, the secondary task was completed within parameters over 84 percent of the time. A primary task requiring a higher mental or physical workload or a more complicated secondary task may have produced a more clear definition of secondary task performance for Cooper-Harper level I, II, and III.

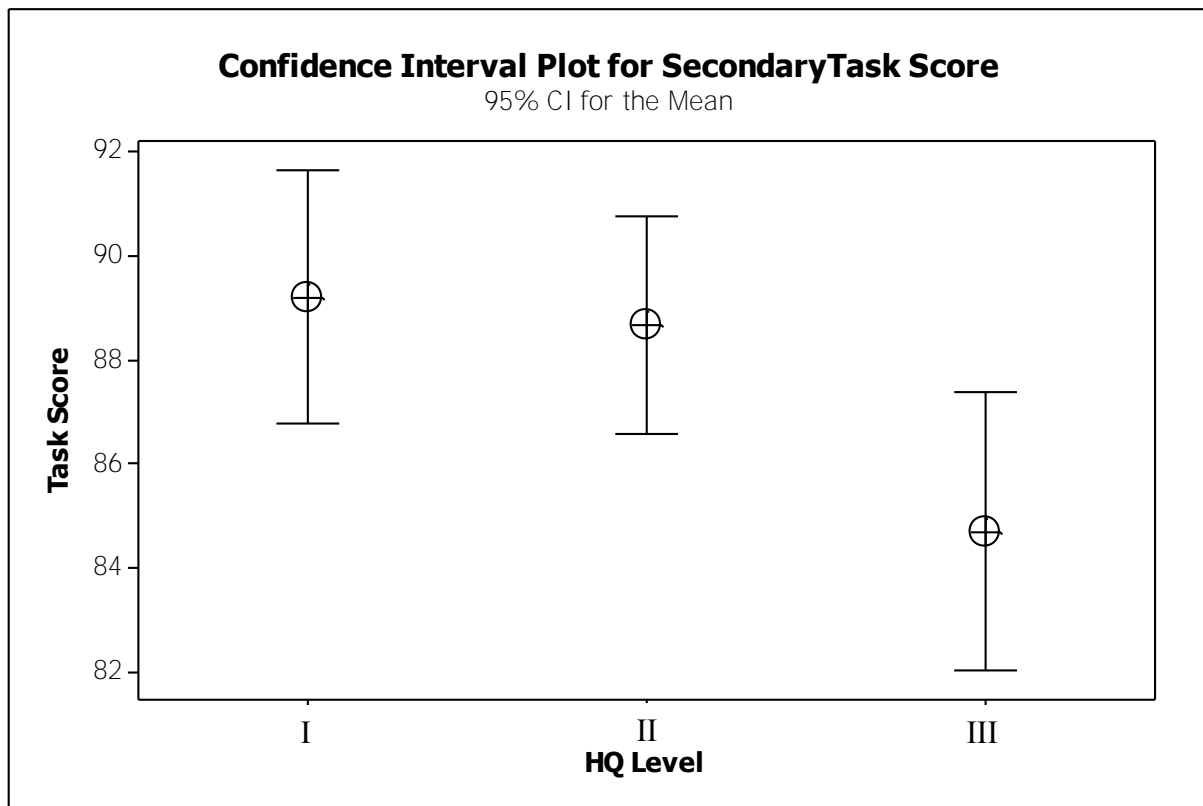


Figure 8. Mean Secondary Task Performance with Confidence Intervals

PIOR Analysis

The PIORs collected for stick and rate coupling configurations reflected a trend of an increasing susceptibility to pilot in the loop oscillations with an increase in the magnitude of inter-axis coupling. The off-axis coupling induced via stick and rate coupling produced undesirable motions at all gain levels tested. As the gain was increased, the off-axis coupling increased and required a larger stick deflection to counter the un-commanded pitch or roll rate. The baseline configuration along with level I stick and rate coupling configurations did not exhibit oscillations. As the cross-coupling increased through levels II and III, the tendency for oscillations to develop was reflected in the PIORs. However, the pilot comments provided a more definite indication of increased susceptibility to PIOR. An example of pilot comments associated with similar configurations with increasing cross-coupling values follows. Configurations 802 and 832 were both pitch due to roll with a gain of 0.5. Each was given a PIOR of 2 and had pilot comments including: “mild pitch due to roll” and “undesirable motion was minor and annoying”. Configurations 810 and 840 (both pitch due to roll with a gain of 2.5) were given a PIOR of 4 and 3, respectively. Pilot comments for 810 and 840 included: “abrupt motion present...bounded PIO when rolling”, “sacrificing performance for compensation of cross coupling motions”, and “pitch due to roll present but predictable, some oscillations occurred but only under tight control”.

The stick and rate bias cross-coupling configurations did not exhibit a tendency for PIO. However, a noticeable change in the configuration effects on PIOR occurred when filters were evaluated during the second and third handling qualities flight for each evaluation pilot. The evaluation pilots commented during debrief that the filters increased the likelihood for oscillations during the primary task. The function of the filters was such that as the pilot introduced compensation for the perceived cross-coupling, the filter would engage and the pilot would need to compensate again for a change in aircraft response. The predictability of the cross-coupling was degraded, which in turn degraded the pilot’s ability to anticipate the compensation needed during execution of the primary task. As an example, configuration 848 (1.25 *da_per_q_rt*) was rated as a level II with PIOR varying between 2 and 3. Pilot comments associated included: “every pitch maneuver saw coupling, roll due to pitch”, “minimal compensation, slight roll due to pitch”, and “pilot in the loop able to compensate for cross coupling, was controllable”. However, with the filters applied to the same configuration (now 879 and 880), the CHRs jumped from level II to III and PIORs varied between 3 and 5. Pilot comments now included: “extensive pilot compensation for jerkiness”, “felt that high gain would cause divergent oscillations”, and “ratchety in roll, bounded PIO observed, had to reduce gain”. Overall, the application of filters produced an undesirable reduction in predictability of the cross-coupling and increased the likelihood of a PIO.

Evaluation of the Use of the ADS-33E-PRF Specification (paragraph 3.4.5.4) as a Potential Metric for Fixed-Wing Aircraft

The CHRs assigned to the test configurations did not exactly match the Cooper-Harper level regions on the ADS-33E-PRF specification (paragraph 3.4.5.4). The regions developed for paragraph 3.4.5.4 of ADS-33E-PRF were based on rotorcraft, and as can be seen in figure 9, the regions drawn from the results of this test were different, as expected.

For stick and rate coupling configurations, the CHRs followed an increasing trend with increasing coupling. The regions were consistent for these two types of induced coupling. Overall, for stick and rate coupling with no bias or filters, use of the ADS-33E-PRF specification (paragraph 3.4.5.4) data reduction and analysis method was promising. Some limitations were identified when considering filter dynamics and bias-induced coupling, meaning that the metric did not fully characterize the aircraft response described by pilot comments. For details about metric usage, possible areas of further investigation, and suggested modifications see appendix P.

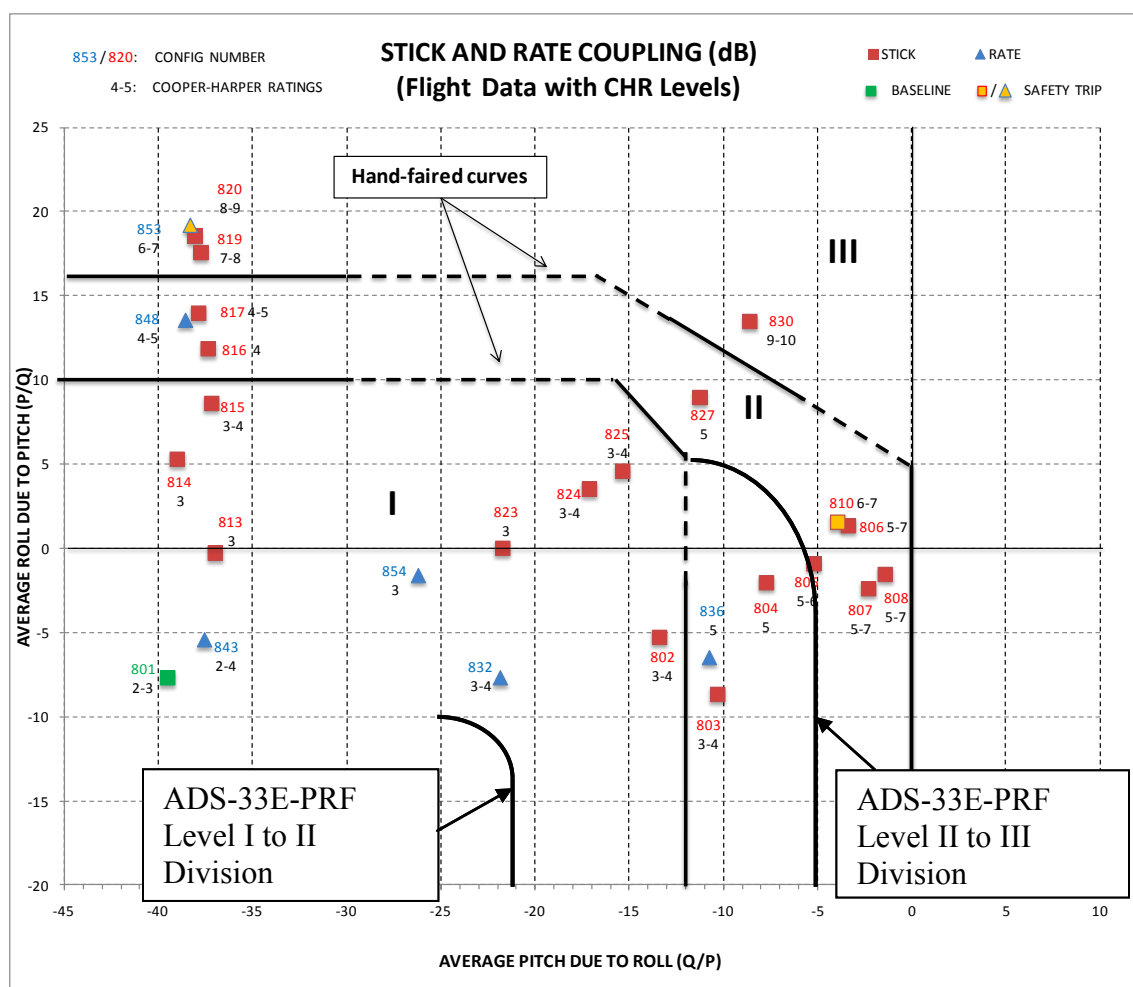


Figure 9. Comparison to ADS-33E-PRF Specification (paragraph 3.4.5.4)

This page was intentionally left blank.

REFERENCES

1. Klyde, David H. and Mitchell, David G., *Handling Quality Demonstration Maneuvers for Fixed Wing Aircraft*, WL-TR-97-3100, Flight Dynamics Directorate, Wright Laboratory, Wright Patterson AFB, Ohio, Oct 1997.
2. United States Army Aviation and Missile Command. ADS-33E-PRF, *Handling Qualities Requirements for Military Rotorcraft*. Mar 2000.
3. Nguyen et al., “Dynamics and Adaptive Control for Stability Recovery of Damaged Asymmetric Aircraft.” AIAA 2006-6049 Presented at the AIAA Guidance, Navigation, and Control Conference and Exhibit, Keystone, Colorado, 21-24 August 2006.
4. Department of Defense. MIL-STD-1797B, *Flying Qualities of Piloted Aircraft*. Feb 2006.
5. Blanken et al., “Rotorcraft Pitch-Roll Decoupling Requirements from a Roll Tracking Maneuver.” Presented at the American Helicopter Society 50th Annual Forum, Washington DC, 11-13 May 1994.
6. Calspan Corporation. WI-FRG-NF-16D-0064-R07, VISTA/NF16D VISTA Simulation System Pilot's Operating Manual. Apr 2009.
7. Mitchell, David G. “Washout Filter Designs” Memorandum. 28 May 2010.

This page was intentionally left blank.

APPENDIX A: COMPLETED TEST CONFIGURATION MATRIX

Table A-1: Completed Test Configuration Matrix

FLOWN	PLANNED	TYPE	OPEN-LOOP (SIM)	CHART	OPEN-LOOP (FLIGHT)				CLOSED LOOP (FLIGHT)								
					FTE 1	FTE 2	FTE 3	CHART	Pilot A			Pilot B			Pilot C		
					#2	#1 #12	#3		#6	#7	#13	#4	#9	#10	#5	#8	#11
801	801	Baseline				o		o	oo	oo	o	oo	oo	oo	ooo	oo	oo
802	802	S T I Q / C P K	o	o		o		o	o			o			o		
803	803		o	o		o		o	o			oo			o		
804	804		o	o		o		o	o			o			o		
805	805		o	o		TRIP		o	o			o			o		
806	806		o	o		TRIP		o	o			o			o		
807	807		o	o		TRIP		o		o	o				TRIP		
808	808		o	o		TRIP		o	TRIP	o					o		
809	809													o			
810	810		o	o		TRIP		o	TRIP		o				TRIP		
811	811					TRIP											o
812	812	S T I P / C Q K															
813	813		o	o		o		o	o			o			o		
814	814		o	o		o		o	o	o		o			o		
815	815		o	o		o		o	o			o			o		
816	816		o	o		o		o	TRIP	o		o			o		
817	817		o	o		o		o	o			o			o		
818	818		TRIP	o						o							o
819	819		o	o		TRIP		o	o			o			o		
820	820		o	o		TRIP		o	o			o			oo		
821	821	S B O T I C H K															
822	822														o		
823	823		o	o		o		o	o			o			o		
824	824		o	o		o		o	o			o			o		
825	825		o	o		o		o	o			o			o		
826	826																
827	827		o	o		o		o		o	o				o		
828	828		TRIP	o						o				oo			o
829	829		TRIP	o						TRIP				o			o
830	830		o	o		o		o	TRIP		o				TRIP		
831	831	R Q / P A T E															
832	832		o	o			o	o		o		o				o	
833	833																
834	834																
835	835																
836	836		o	o			o	o	o			o				o	
837	837																
838	838																
839	839																
840	840		o	o			NODATA			o		o				o	
841	841	R P / Q A T E															
842	842																
843	843		o	o			o	o		o		o				o	
844	844																
845	845																
846	846																
847	847																
848	848		o	o			o	o		o		o				o	
849	849																
850	850																
851	851																

FLOWN	PLANNED	TYPE	OPEN-LOOP (SIM)	CHART	OPEN-LOOP (FLIGHT)				TRACKING TASK (FLIGHT)								
					FTE 1	FTE 2	FTE 3	CHART	Pilot A			Pilot B			Pilot C		
					#2	#1 #12	#3		#6	#7	#13	#4	#9	#10	#5	#8	#11
852	852																
853	853		NO DATA				TRIP	o		TRIP			o			o	
854	854	ROTHE	o	o			o	o		o			o			o	
855	855																
856	856		o	o			NODATA			o			o			o	
857	857																
858	858																
859	859		TRIP	o			NODATA			o			TRIP			TRIP	
860	860																
861	861	FILTERS*	o	o			o	o			o		o			o	
862	862		o	o			TRIP	o			o		o			o	
863	863		o	o		o		o					o				o
864	864		o	o		TRIP		o			o		o				
865	865					TRIP							o				
866	866		o	o		TRIP		o					o				TRIP
867	867		o	o			NODATA			o			o			o	
868	868		o	o			NODATA			TRIP			o			TRIP	
869	869		o	o			o	o		o			o			o	
870	870		o	o			o	o		o			o			o	
871	871		o	o		o		o					o				o
872	872		o	o		o		o					o				o
873	873		o	o		NO DATA					o						o
874	874													o			
875	875		o	o			o	o		o			o			o	
876	876		o	o			TRIP	o			o		o				o
877	877	FILTERS*	o	o		TRIP		o					o				o
878	878					TRIP							o				o
879	879		o	o			o	o			o		o				o
880	880		o	o			TRIP	o			o		o				o
881	881												o				o
882	882		o	o									o				o
883	883		o	o			NO DATA				o		o				o
884	884		o	o							o		o				o
885	885	STICK															
886	886		o	o							o		o				o
887	887																
888	888	BRATE	TRIP	o						o			o				TRIP
889	889																
890	890		o	o							o		o				o
891	891																
892	892		TRIP	o							o		o				o

	Planned Test Point
	Executed Test Point (only one pilot)
	Executed Test Point (at least two pilots)
*	Filters' open-loop data obtained in simulation with safety trips disabled
o	Data available (open-loop and/or closed-loop)
TRIP	Safety trip triggered (enough data collected during the sweeps)
TRIP / o	Safety trip triggered (less than 50% data collected during the sweeps)
NO DATA	Safety trip triggered (data unreliable)
	Not attempted

APPENDIX B: CONFIGURATION GAIN MATRICES

Table B-3: Stick and Rate Coupling Configuration Gain Matrix

STICK COUPLING			RATE COUPLING		
SIMULINK NAME MFD NAME	pitch_per_roll_rt XE/DAS	roll_per_pitch_rt XA/DES	SIMULINK NAME MFD NAME	de_per_p_rt XE/P	da_per_q_rt XA/Q
801	0	0	801	0	0
802	0.50	0	831	0.25	0
803	0.75	0	832	0.50	0
804	1.00	0	833	0.75	0
805	1.25	0	834	1.00	0
806	1.50	0	835	1.25	0
807	1.75	0	836	1.50	0
808	2.00	0	837	1.75	0
809	2.25	0	838	2.00	0
810	2.50	0	839	2.25	0
811	2.75	0	840	2.50	0
812	3.00	0	841	2.75	0
813	0	0.25	842	3.00	0
814	0	0.50	843	0	0.10
815	0	0.75	844	0	0.25
816	0	1.00	845	0	0.50
817	0	1.25	846	0	0.75
818	0	1.50	847	0	1.00
819	0	1.75	848	0	1.25
820	0	2.00	849	0	1.50
821	0	2.25	850	0	1.75
822	0	2.50	851	0	2.00
823	0.25	0.25	852	0	2.25
824	0.40	0.40	853	0	2.50
825	0.50	0.50	854	0.25	0.25
826	0.60	0.60	855	0.50	0.50
827	0.75	0.75	856	0.75	0.75
828	0.80	0.80	857	1.00	1.00
829	0.90	0.90	858	1.25	1.25
830	1.00	1.00	859	1.50	1.50
			860	1.75	1.75

cs_angle_rt = 0
 pitch_delay_rt = 0
 roll_delay_rt = 0
 pitch_bias_rt = 0
 roll_bias_rt = 0
 pitch_filt_A_rt = 0
 pitch_filt_B_rt = 0
 pitch_filt_C_rt = 1
 pitch_filt_D_rt = 0
 pitch_filt_E_rt = 0
 pitch_filt_F_rt = 1
 roll_filt_A_rt = 0
 roll_filt_B_rt = 0
 roll_filt_C_rt = 1
 roll_filt_D_rt = 0
 roll_filt_E_rt = 0
 roll_filt_F_rt = 1

de_per_p_nom_rt = 0.1
 da_per_q_nom_rt = 0.36
 q_delay_rt = 0
 p_delay_rt = 0
 qdot_bias_rt = 0
 pdot_bias_rt = 0
 q_filt_A_rt = 0
 q_filt_B_rt = 0
 q_filt_C_rt = 1
 q_filt_D_rt = 0
 q_filt_E_rt = 0
 q_filt_F_rt = 1
 p_filt_A_rt = 0
 p_filt_B_rt = 0
 p_filt_C_rt = 1
 p_filt_D_rt = 0
 p_filt_E_rt = 0
 p_filt_F_rt = 1

Table B-4: Stick and Rate Filter Coupling and Bias Configuration Gain Matrix

STICK FILTERS																															
SIMULINK NAME	MFD NAME	NONFILTERED	CONFIG	pitch_per_roll_rt	XEIDAS	roll_per_pitch_rt	XADES	pitch_filt_A_rt	XE FILT A	pitch_filt_B_rt	XE FILT B	pitch_filt_C_rt	XE FILT C	pitch_filt_D_rt	XE FILT D	pitch_filt_E_rt	XE FILT E	pitch_filt_F_rt	XE FILT F	roll_filt_A_rt	XA FILT A	roll_filt_B_rt	XA FILT B	roll_filt_C_rt	XA FILT C	roll_filt_D_rt	XA FILT D	roll_filt_E_rt	XA FILT E	roll_filt_F_rt	XA FILT F
801		0	0	0	0	1	0	0	1	0	0	1	0	0	1	0	0	0	1												
861	802	0.50	0	0	0	1	0	0	1	0	0	1	0	25	0	1	6	25													
862		0.50	0	0	0	1	0	0	1	0	0	1	0	100	0	1	12	100													
863	803	0.75	0	0	0	1	0	0	1	0	0	1	0	25	0	1	6	25													
864		0.75	0	0	0	1	0	0	1	0	0	1	0	100	0	1	12	100													
865	804	1.00	0	0	0	1	0	0	1	0	0	1	0	25	0	1	6	25													
866		1.00	0	0	0	1	0	0	1	0	0	1	0	100	0	1	12	100													
867	805	1.25	0	0	0	1	0	0	1	0	0	1	0	25	0	1	6	25													
868		1.25	0	0	0	1	0	0	1	0	0	1	0	100	0	1	12	100													
869	813	0	0.25	0	25	0	1	6	25	0	0	1	0	0	1	0	0	1													
870		0	0.25	0	100	0	1	12	100	0	0	1	0	0	1	0	0	1													
871	814	0	0.50	0	25	0	1	6	25	0	0	1	0	0	1	0	0	1													
872		0	0.50	0	100	0	1	12	100	0	0	1	0	0	1	0	0	1													
873	815	0	0.75	0	25	0	1	6	25	0	0	1	0	0	1	0	0	1													
874		0	0.75	0	100	0	1	12	100	0	0	1	0	0	1	0	0	1													
875	816	0	1.00	0	25	0	1	6	25	0	0	1	0	0	1	0	0	1													
876		0	1.00	0	100	0	1	12	100	0	0	1	0	0	1	0	0	1													

cs_angle_rt = 0
pitch_delay_rt = 0
roll_delay_rt = 0
pitch_bias_rt = 0
roll_bias_rt = 0

RATE FILTERS																													
SIM/LINK NAME	MFD NAME	NON FILTERED	CONFIG	da_per_p.rt	da_per_q.rt	q_filt_A.rt	Q_FILTA	q_filt_B.rt	Q_FILTB	q_filt_C.rt	Q_FILTC	q_filt_D.rt	Q_FILTD	q_filt_E.rt	Q_FILTE	q_filt_F.rt	Q_FILTF	p_filt_A.rt	P_FILTA	p_filt_B.rt	P_FILTB	p_filt_C.rt	P_FILTC	p_filt_D.rt	P_FILTD	p_filt_E.rt	P_FILTE	p_filt_F.rt	P_FILTF
801		0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	1					
877	847	0	1	0	25	0	1	6	25	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1					
878		0	1	0	100	0	1	12	100	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1					
879	848	0	1.25	0	25	0	1	6	25	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1					
880		0	1.25	0	100	0	1	12	100	0	0	1	0	0	1	0	0	1	0	0	1	0	0	1					
881	835	1.25	0	0	0	0	1	0	0	1	0	0	1	0	0	25	0	1	6	25									
882		1.25	0	0	0	0	1	0	0	1	0	0	1	0	0	100	0	1	12	100									
883	836	1.50	0	0	0	0	1	0	0	1	0	0	1	0	0	25	0	1	6	25									
884		1.50	0	0	0	0	1	0	0	1	0	0	1	0	0	100	0	1	12	100									

da_per_p_nom_rt = 0.1
da_per_q_nom_rt = 0.36
q_delay_rt = 0
p_delay_rt = 0
qdot_bias_rt = 0
pdot_bias_rt = 0

STICK BIAS			
SIMULINK NAME	MFD NAME	pitch_bias_rt	roll_bias_rt
		XE BIAS	XA BIAS
801	0	0	
885	0.25	0	
886	0.50	0	
887	0	0.25	
888	0	0.50	

RATE BIAS					
SIMULINK NAME	MFD NAME	qdrot_bias_rt	QDROT BIAS	pdrot_bias_rt	PDROT BIAS
801	0	0			
889	3.00	0			
890	6.00	0			
891	0	2.00			
892	0	4.00			

APPENDIX C: GAIN NAME REFERENCE LIST

All of the cross-coupling gains in the Icarus FCS are listed in the following tables. The „SIMULINK® Name“ is the name for the gain in SIMULINK® which was used with the TPS HQ simulator. The „MFD Name“ is the name for the gain as it showed on the Configuration Control System (CCS) page of the MFD in VISTA. The MFD Scale was the scaling used to convert the gain from Engineering to CCS units on the MFD. For example, to set a gain to a value of 5 if MFD Scale was 1, the gain was set to 005, if 10 set to 050, if 100 set to 500, etc.

Table C-1: Stick Coupling Gains

SIMULINK® Name	Description	MFD Name	MFD Scale
cs_angle_rt	Stick Rotation Angle (deg , +CW)	CS ANGLE	1
pitch_per_roll_rt	Roll Stick to Pitch Stick Coupling Gain	XE/DAS	100
roll_per_pitch_rt	Pitch Stick to Roll Stick Coupling Gain	XA/DES	100
pitch_delay_rt	Pitch Stick to Roll Stick Time Delay	XE DELAY	1000
roll_delay_rt	Roll Stick to Pitch Stick Time Delay	XA DELAY	1000
pitch_bias_rt	Pitch Stick Bias	XE BIAS	100
roll_bias_rt	Roll Stick Bias	XA BIAS	100
pitch_filt_A_rt	Pitch Stick to Roll Stick Filter Coefficient A	XE FILT A	1
pitch_filt_B_rt	Pitch Stick to Roll Stick Filter Coefficient B	XE FILT B	1
pitch_filt_C_rt	Pitch Stick to Roll Stick Filter Coefficient C	XE FILT C	1
pitch_filt_D_rt	Pitch Stick to Roll Stick Filter Coefficient D	XE FILT D	1
pitch_filt_E_rt	Pitch Stick to Roll Stick Filter Coefficient E	XE FILT E	1
pitch_filt_F_rt	Pitch Stick to Roll Stick Filter Coefficient F	XE FILT F	1
roll_filt_A_rt	Roll Stick to Pitch Stick Filter Coefficient A	XA FILT A	1
roll_filt_B_rt	Roll Stick to Pitch Stick Filter Coefficient B	XA FILT B	1
roll_filt_C_rt	Roll Stick to Pitch Stick Filter Coefficient C	XA FILT C	1
roll_filt_D_rt	Roll Stick to Pitch Stick Filter Coefficient D	XA FILT D	1
roll_filt_E_rt	Roll Stick to Pitch Stick Filter Coefficient E	XA FILT E	1
roll_filt_F_rt	Roll Stick to Pitch Stick Filter Coefficient F	XA FILT F	1
de_per_p_nom_rt	Nominal Elevator per Roll Rate Gain	XE/P NOM	100
da_per_q_nom_rt	Nominal Aileron per Pitch Rate Gain	XA/Q NOM	100
de_per_p_rt	Elevator per Roll Rate Scaling	XE/P	100
da_per_q_rt	Aileron per Pitch Rate Scaling	XA/Q	100
q_delay_rt	Pitch Rate to Aileron Time Delay	Q DELAY	1000
p_delay_rt	Roll Rate to Elevator Time Delay	P DELAY	1000
qdot_bias_rt	Elevator Command Bias	QDOT BIAS	10
pdot_bias_rt	Aileron Command Bias	PDOT BIAS	10
q_filt_A_rt	Pitch Rate to Aileron Filter Coefficient A	Q FILT A	1
q_filt_B_rt	Pitch Rate to Aileron Filter Coefficient B	Q FILT B	1
q_filt_C_rt	Pitch Rate to Aileron Filter Coefficient C	Q FILT C	1
q_filt_D_rt	Pitch Rate to Aileron Filter Coefficient D	Q FILT D	1
q_filt_E_rt	Pitch Rate to Aileron Filter Coefficient E	Q FILT E	1
q_filt_F_rt	Pitch Rate to Aileron Filter Coefficient F	Q FILT F	1
p_filt_A_rt	Roll Rate to Elevator Filter Coefficient A	P FILT A	1
p_filt_B_rt	Roll Rate to Elevator Filter Coefficient B	P FILT B	1
p_filt_C_rt	Roll Rate to Elevator Filter Coefficient C	P FILT C	1
p_filt_D_rt	Roll Rate to Elevator Filter Coefficient D	P FILT D	1
p_filt_E_rt	Roll Rate to Elevator Filter Coefficient E	P FILT E	1
p_filt_F_rt	Roll Rate to Elevator Filter Coefficient F	P FILT F	1

This page was intentionally left blank.

APPENDIX D: FLYING QUALITIES DATA

The following table includes the results of the data reduction of the frequency sweeps. These are the values for the test points plotted in appendix F.

Table D-1: Flying Qualities Data

		dB Scale						Linear Scale						
		SIM				FLIGHT		SIM				FLIGHT		
		CFG	q/p (p2r)	p/q (r2p)		CFG	q/p	p/q	CFG	p/p (r2rp/q (r2p)	CFG	q/p	p/q	
1	Q / P	STICK	Baseline	-49.7	-325.1	Baseline	-39.5	-7.7	Baseline	0.003	0.000	Baseline	0.011	0.413
2			802	-12.3	-325.1	802	-13.4	-5.3	802	0.244	0.000	802	0.213	0.545
3			803	-8.7	-324.4	803	-10.3	-8.7	803	0.366	0.000	803	0.305	0.369
4			804	-6.2	-331.0	804	-7.7	-2.0	804	0.489	0.000	804	0.410	0.793
5			805	-4.3	-328.2	805	-5.2	-0.9	805	0.612	0.000	805	0.549	0.903
6			806	-2.7	-315.8	806	-3.4	1.4	806	0.735	0.000	806	0.677	1.169
7			807	-1.4	-311.3	807	-2.3	-2.4	807	0.854	0.000	807	0.767	0.762
8			808	-0.3	-309.5	808	-1.4	-1.5	808	0.967	0.000	808	0.851	0.833
9			810	1.2	-312.2	810	-4.0	1.5	810	1.147	0.000	810	0.635	1.195
10			P / Q	813	-49.7	-3.4	813	-37.0	-0.3	813	0.003	0.676	813	0.014
11	814	-49.6		2.6	814	-39.0	5.3	814	0.003	1.352	814	0.011	1.841	
12	815	-49.8		6.1	815	-37.2	8.6	815	0.003	2.027	815	0.014	2.693	
13	816	-49.6		8.6	816	-37.4	11.9	816	0.003	2.699	816	0.013	3.921	
14	817	-49.8		10.6	817	-37.9	14.0	817	0.003	3.371	817	0.013	5.013	
15	818	-43.5		10.6	818			818	0.007	3.392	818			
16	819	-49.8		13.5	819	-37.8	17.6	819	0.003	4.708	819	0.013	7.587	
17	BOTH	820	-49.7	14.6	820	-38.1	18.6	820	0.003	5.367	820	0.012	8.507	
18		823	-18.3	-3.4	823	-21.7	0.0	823	0.122	0.676	823	0.082	1.002	
19		824	-14.2	0.7	824	-17.2	3.5	824	0.195	1.082	824	0.139	1.501	
20		825	-12.3	2.6	825	-15.4	4.6	825	0.244	1.352	825	0.171	1.706	
21		827	-8.7	6.1	827	-11.3	9.0	827	0.366	2.027	827	0.272	2.816	
22		828	-9.0	6.2	828			828	0.354	2.049	828			
23		829	-7.5	7.8	829			829	0.420	2.446	829			
24	R / P	830	-6.2	8.6	830	-8.7	13.5	830	0.489	2.700	830	0.369	4.737	
25		832	-18.6	-329.6	832	-21.9	-7.6	832	0.118	0.000	832	0.081	0.415	
26		836	-9.8	-335.0	836	-10.7	-6.5	836	0.323	0.000	836	0.290	0.474	
27		840	-10.1	-336.6	840			840	0.312	0.000	840			
28		843	-45.9	-12.3	843	-37.6	-5.4	843	0.005	0.243	843	0.013	0.537	
29		848	-50.7	15.8	848	-38.6	13.6	848	0.003	6.152	848	0.012	4.780	
30		853			853	-38.3	19.2	853			853	0.012	9.133	
31	BOTH	854	-24.5	-4.2	854	-26.2	-1.6	854	0.059	0.616	854	0.049	0.829	
32		856	-15.9	3.1	856			856	0.160	1.431	856			
33		859	-15.4	11.1	859			859	0.169	3.598	859			
34	FILTERS	STICK	861	-3.8	-332.6	861	-2.1	-10.8	861	0.643	0.000	861	0.789	0.289
35			862	-4.0	-336.0	862	-2.6	-6.5	862	0.633	0.000	862	0.740	0.471
36			863	-5.4	-332.6	863	1.2	-8.3	863	0.540	0.000	863	1.149	0.387
37			864	-4.9	-336.8	864	-6.8	-1.8	864	0.567	0.000	864	0.459	0.817
38			866	-6.6	-332.6	866	-4.8	-4.2	866	0.466	0.000	866	0.576	0.615
39			867	-8.6	-325.7	867			867	0.370	0.000	867		
40			868	-7.8	-330.2	868			868	0.409	0.000	868		
41			869	-44.1	6.7	869	-39.3	7.9	869	0.006	2.157	869	0.011	2.482
42			870	-44.0	9.0	870	-39.8	8.4	870	0.006	2.809	870	0.010	2.621
43			871	-44.6	12.7	871	-41.6	15.1	871	0.006	4.298	871	0.008	5.691
44	872	-44.3	14.3	872	-41.4	15.6	872	0.006	5.175	872	0.008	6.045		
45	R / P	873	-44.6	15.9	873			873	0.006	6.246	873			
46		875	-42.7	17.6	875	-40.0	21.0	875	0.007	7.597	875	0.010	11.248	
47		876	-44.5	17.9	876	-36.7	22.9	876	0.006	7.847	876	0.015	13.902	
48		877	-41.1	17.8	877	-37.0	19.4	877	0.009	7.768	877	0.014	9.369	
49		879	-37.7	18.3	879	-37.3	22.2	879	0.013	8.229	879	0.014	12.858	
50		880	-36.9	14.9	880	-34.3	22.6	880	0.014	5.573	880	0.019	13.443	
51		FILTERS	882	3.6	-332.9	882			882	1.514	0.000	882		
52	883		3.4	-315.6	883			883	1.471	0.000	883			
53	884		3.7	-324.8	884			884	1.535	0.000	884			
54	886		-40.3	-318.1	886			886	0.010	0.000	886			
55	BIAS	888	-0.1	4.1	888			888	0.993	1.608	888			
56		890	-41.2	-315.2	890			890	0.009	0.000	890			
57	BIAS	892	-15.6	3.5	892			892	0.166	1.494	892			

Data unreliable or test point not attempted

Safety tripped during the frequency sweeps, location not reliable

This page was intentionally left blank.

APPENDIX E: HANDLING QUALITIES DATA

Table E-1: Handling Qualities Data

CONFIGURATION NUMBER	PILOT	PRIMARY TASK COMPOSITE	SECONDARY TASK SCORE	CHR	PIOR	PITCH PERF D	PITCH PERF A	ROLL PERF D	ROLL PERF A
802	A	60	83	3	1	79	93	76	86
	B	53	93	4	2	72	91	72	86
	C	57	98	3	2	77	92	76	88
803	A	45	75	4	2	65	88	68	87
	B	40	85	3	2	71	91	69	83
	C	48	45	4	2	67	89	70	90
804	A	50	73	5	4	67	88	75	90
	B	47	80	5	3	61	85	73	85
	C	46	95	5	2	62	83	70	88
805	A	52	70	6	4	67	87	73	88
	B	45	75	5	3	58	78	74	85
	C	49	95	5	2	62	84	75	86
806	A	48	83	6	4	64	85	70	86
	B	41	78	7	4	57	81	64	84
	C	46	98	5	2	62	90	69	87
807	A	-	-	-	-	-	-	-	-
	A	-	-	-	-	-	-	-	-
	A	39	85	7	3	54	76	68	87
	B	42	85	7	3	57	80	71	83
	C	43	87	5	2	53	81	75	90
808	A	40	83	7	3	55	75	67	89
	B	43	75	6	3	58	78	65	82
	C	42	98	5	2	56	82	73	86
809	A								
	B	23	78	7	3	40	65	53	79
	C								
810	A	39	88	7	4	49	74	71	87
	B	31	68	7	4	45	70	64	83
	C	38	88	6	3	50	74	70	89
811	A								
	B								
	C	34	94	8	5	42	64	76	89
813	A	57	80	3	2	74	91	75	84
	B	52	95	3	2	73	93	67	84
	C	57	85	3	2	78	96	76	88
814	A	53	93	3	1	73	92	74	86
	B	58	65	3	2	72	90	76	89
	C	56	93	3	2	77	93	74	87
815	A	60	53	3	2	78	94	78	87
	B	53	80	4	2	72	92	71	86
	C	59	98	3	2	77	93	77	87
816	A	-	-	-	-	-	-	-	-
	A	57	98	4	2	77	93	75	86
	B	53	85	4	2	71	92	74	85
	C	57	88	4	2	74	92	76	86

CONFIGURATION NUMBER	PILOT	PRIMARY TASK COMPOSITE	SECONDARY TASK SCORE	CHR	PIOR	PITCH PERF D	PITCH PERF A	ROLL PERF D	ROLL PERF A
817	A	53	85	5	3	73	91	73	88
	B	55	85	4	2	76	91	72	86
	C	61	98	4	2	76	93	79	88
818	A	50	95	6	3	71	88	68	85
	B								
	C	55	95	4	3	74	93	76	89
819	A	48	78	7	4	71	91	69	87
	B	50	68	8	3	72	86	71	85
	C	56	93	3	2	72	92	78	89
820	A	39	85	9	3	62	82	59	81
	B	54	65	8	4	70	86	74	85
	C	46	85	4	2	70	87	69	87
	C	45	82	5	2	68	91	67	86
822	A								
	B								
	C	47	90	5	2	66	91	74	86
823	A	59	80	3	1	81	92	73	86
	B	61	90	3	2	78	93	79	87
	C	57	93	3	2	79	94	75	86
824	A	52	63	4	3	73	92	74	86
	B	58	73	3	2	80	94	74	86
	C	57	90	3	2	76	94	76	88
825	A	52	70	4	3	72	90	73	88
	B	51	85	3	2	72	89	72	85
	C	52	100	3	2	74	92	73	86
827	A	37	85	5	3	57	78	60	82
	B	47	75	5	2	72	89	67	85
	C	45	73	5	3	64	87	69	86
828	A	35	88	6	3	59	79	53	76
	B	34	85	6	3	57	77	53	83
	C	38	85	6	3	56	81	67	85
829	A	24	88	-	-	-	-	51	80
	B	19	70	7	3	42	71	46	75
	C	23	77	7	3	38	64	58	89
830	A	46	75	10	-	46	72	100	100
	B	6	14	9	4	11	24	33	56
	C								

CONFIGURATION NUMBER	PILOT	PRIMARY TASK COMPOSITE	SECONDARY TASK SCORE	CHR	PIOR	PITCH PERF D	PITCH PERF A	ROLL PERF D	ROLL PERF A
832	A	62	88	3	1	74	91	80	88
	B	53	98	4	2	68	90	75	89
	C	54	95	4	2	70	90	73	88
836	A	52	95	5	2	61	84	78	86
	B	42	98	5	2	62	83	66	87
	C	45	88	5	3	61	81	70	87
840	A	38	95	7	4	48	75	74	88
	B	29	95	7	3	40	65	65	84
	C	32	80	7	3	39	64	72	88
843	A	64	80	3	1	84	94	76	87
	B	55	95	2	1	72	94	72	85
	C	54	88	4	2	75	92	71	86
848	A	57	88	5	2	80	93	72	88
	B	52	98	4	2	76	94	71	88
	C	54	85	5	3	69	86	78	88
853	A	45	94	7	3	67	82	65	86
	B	45	95	6	3	72	92	64	89
	C	39	80	7	3	61	80	64	87
854	A	61	90	3	1	78	91	77	87
	B	60	98	3	2	75	94	78	88
	C	61	93	3	2	77	94	77	88
856	A	51	97	5	3	67	90	75	88
	B	41	90	5	2	61	86	62	86
	C	40	98	5	3	61	85	71	88
859	A	20	98	9	6	40	68	46	75
	B	100	0	10	-	-	-	-	-
	C	13	0	-	-	-	-	53	82

CONFIGURATION NUMBER	PILOT	PRIMARY TASK COMPOSITE	SECONDARY TASK SCORE	CHR	PIOR	PITCH PERF D	PITCH PERF A	ROLL PERF D	ROLL PERF A
861	A	38	88	3	2	66	87	58	86
	B	42	100	5	2	67	89	65	81
	C	48	95	5	3	64	87	73	85
862	A	33	90	3	2	67	86	55	83
	B	41	95	5	3	59	84	68	84
	C	41	84	7	3	59	83	69	87
863	A								
	B	32	95	5	3	56	84	56	74
	C	37	75	7	3	52	79	67	84
864	A	32	100	-	-	-	-	54	84
	B	31	94	7	3	50	76	61	86
	C								
865	A								
	B	22	88	7	3	51	76	47	77
	C								
866	A								
	B	19	97	7	3	44	74	45	83
	C	27	90	7	3	41	66	65	90
867	A	21	98	6	4	40	67	55	81
	B	23	88	7	3	47	72	52	82
	C	25	85	8	5	36	68	61	82
868	A	-	-	-	-	-	-	-	-
	A	2	75	10	5	11	27	17	100
	B	19	83	7	3	41	67	40	71
	C	-	-	-	-	-	-	-	-
	C	7	0	-	-	-	-	54	96
869	A	56	98	4	2	77	93	73	86
	B	60	98	3	2	77	92	78	87
	C	61	93	4	3	80	92	76	87
870	A	53	93	4	2	77	92	71	87
	B	50	98	4	2	74	90	72	87
	C	55	95	5	3	71	91	79	87
871	A								
	B	46	100	4	2	74	90	64	84
	C	47	78	5	3	61	90	76	87
872	A								
	B	41	88	4	3	72	92	59	83
	C	50	90	4	3	74	89	73	87

CONFIGURATION NUMBER	PILOT	PRIMARY TASK COMPOSITE	SECONDARY TASK SCORE	CHR	PIOR	PITCH PERF D	PITCH PERF A	ROLL PERF D	ROLL PERF A
873	A	46	98	4	3	70	85	66	82
	A	59	99	4	3	77	90	66	82
	B								
	C	46	83	5	3	62	86	71	87
874	A								
	B	37	95	4	3	73	91	57	84
	C								
875	A	45	93	9	5	68	86	69	84
	B	43	98	6	4	68	87	63	80
	C	48	95	5	3	69	87	71	86
876	A	42	90	5	3	69	86	58	78
	B	35	93	6	4	67	88	53	78
	C	52	78	5	3	69	86	76	86
877	A								
	B	36	95	6	5	69	88	55	79
	C	39	88	6	3	57	85	65	84
878	A								
	B	31	88	6	3	59	88	53	75
	C								
879	A	33	93	6	4	67	87	52	80
	B	34	90	5	3	69	89	50	77
	C	39	88	7	5	59	83	62	86
880	A	35	90	7	5	53	81	59	79
	B	33	88	7	4	54	83	56	78
	C	33	71	7	5	57	83	58	80
881	A								
	B	25	100	7	4	55	75	54	80
	C								
882	A								
	B	20	85	7	3	45	76	52	74
	C	27	83	8	5	39	67	69	84
883	A	23	93	5	4	47	73	58	85
	B	20	88	8	5	36	64	53	81
	C	27	88	9	5	36	64	72	86
884	A	22	80	7	4	35	61	59	80
	B	14	75	8	5	32	57	45	71
	C	27	90	9	5	39	65	66	85

CONFIGURATION NUMBER	PILOT	PRIMARY TASK COMPOSITE	SECONDARY TASK SCORE	CHR	PIOR	PITCH PERF D	PITCH PERF A	ROLL PERF D	ROLL PERF A
886	A	53	95	3	1	80	94	68	86
	B	51	88	3	1	76	94	70	88
	C	55	90	4	3	73	88	75	86
888	A	48	88	3	1	76	91	63	85
	B	59	98	3	2	78	92	76	86
	C	61	89	5	3	67	84	84	93
890	A	54	83	3	1	77	88	68	86
	B	58	100	3	1	79	91	74	88
	C	-	-	-	-	-	-	-	-
	C	62	88	4	3	78	91	79	90
892	A	44	95	3	1	70	81	67	85
	B	58	100	3	2	75	94	76	88
	C	-	-	-	-	-	-	-	-
	C	60	88	4	3	79	93	80	90

CONFIGURATION NUMBER	PILOT	PILOT COMMENTS
802	A	Minor pitch due to roll present. desired performance, tolerable workload, minimal compensation
	B	Some pitch due to roll noticed early but very subtle. Performance good but required active compensation. Tolerable workload, moderate compensation
	C	Some pitch due to roll noticeable but subtle and similar to baseline. desired performance, tolerable workload, minimal compensation
803	A	Some pitch due to roll present. The pitching had an annoying bobbing effect. Desired performance, tolerable workload, moderate compensation
	B	Looks like pitch due to roll. More sensitive in roll. Noticeable undesirable motion that tended to occur. desired performance, tolerable workload, minimal compensation
	C	Desired performance, tolerable workload, moderate compensation
804	A	Noticeable pitch due to roll; worse than configuration 825. Had to back out of the loop a little due to the coupling. adequate performance, tolerable workload, considerable compensation (post flight, IP commented that pilot was not in command at all times of aircraft and would argue for a CHR 10)
	B	Much more pronounced pitch due to roll. Did not see dual axis coupling. Want to look at 2nd task performance. Easily induced undesirable motion. CHR given based on pilot compensation vs performance. adequate performance, tolerable workload, considerable compensation
	C	Noticeable pitch due to roll. adequate performance, tolerable workload, considerable compensation
805	A	Pitch due to roll noticeable and worse than configuration 817. adequate performance, tolerable workload, extensive compensation
	B	Wow, definite pitch due to roll! Cross coupling felt more sensitive. Undesirable motion was easily induced. adequate performance, tolerable workload, considerable or maybe extensive compensation
	C	The pitch due to roll is worse than configuration 804. adequate performance, tolerable workload, considerable compensation
806	A	Pitch due to roll noticeable and worse than configuration 823. Had to reboot VSS for vibrational effects. adequate performance, tolerable workload, extensive compensation
	B	Significant pitch due to roll. Under tight control, could get into bounded PIO (post flight, pilot stated based on PIO definitions that bounded PIO was not reached). Adequate performance attained but major deficiencies present. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Pitch due to roll is present. Adequate performance, tolerable workload, considerable compensation
807	A	VSS power supply issues; tried to reset several times but couldn't fix the problem. RTB'd
	A	Strong pitch due to roll present! inadequate performance, intolerable workload, maximum tolerable compensation
	A	Strong pitch due to roll present! Unpredictable motions. Undesirable motions easily induced. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Pitch due to roll present and relatively predictable. Lots of undesirable motion but no PIO. Adequate performance but major deficiencies. inadequate performance, intolerable workload for adequate performance, maximum tolerable compensation
	C	Pitch due to roll noticeable. Rate monitor safety trip at 95 seconds, adequate performance, tolerable workload, considerable compensation
808	A	Pitch due to roll noticeable. Divergent PIO present and lost control of aircraft. Unflyable. Right rate limit monitor trip before completion of task. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Less pronounced pitch due to roll. Easily induced undesirable motions; easier than last. adequate performance, tolerable workload, extensive compensation.
	C	Pitch due to roll noticeable. adequate performance, tolerable workload, considerable compensation
809	A	
	B	Pitch due to roll. S***!!
	C	
810	A	Awful to fly. DFLCC tripped at end of task and had to reset VSS. adequate performance, tolerable workload, maximum tolerable compensation
	B	Abrupt motion present. Pitch due to roll more extreme than configuration 806. Bounded PIO when rolling. Control not in question. inadequate performance, intolerable workload for adequate performance, maximum tolerable compensation
	C	Pitch due to roll obvious. Rate limit safety trip at 1min. 45 seconds, adequate performance, tolerable workload, extensive compensation

811	A	
	B	
	C	Lots of pitch due to roll divergence present. Had to back out of the loop to retain control. Divergent PIOs present. Right stab rate limiter trip at over 1 minute into the task. inadequate performance, intolerable workload, considerable compensation required for control
813	A	Mild roll due to pitch present. desired performance, tolerable workload, minimal compensation
	B	Really subtle cross coupling. Some undesirable motion observed. "Feels like I gave it a better score than it deserved". Terminated early for traffic (1.45 min into task) desired performance, tolerable workload, minimal compensation
	C	No sign of cross coupling. adequate performance, tolerable workload, minimal compensation
814	A	Subtle motion present but difficult to identify. Moderate undesirable motions present. desired performance, tolerable workload, minimal compensation
	B	Subtle motion, hard to identify. Minor undesirable motions present. Terminated task at 2 minutes for traffic. desired performance, tolerable workload, minimal pilot compensation
	C	Dual axis coupling present. desired performance, tolerable workload, minimal compensation
815	A	Definite roll due to pitch present. Better than the configuration 803 single axis coupling. desired performance, tolerable workload, minimal compensation
	B	Subtle cross coupling noticeable. Some undesirable motion present. desired performance, tolerable workload, moderate compensation
	C	More workload required than configuration 813. desired performance, tolerable workload, minimal compensation
816	A	Instant DFLCC trip. Bad power supply, no data.
	A	Definite roll due to pitch present. Easy to predict and no filtering noted. desired performance, tolerable workload, moderate compensation
	B	Undesirable motion tended to occur and active pilot compensation required to compensate for the motion. Performance pretty good. desired performance, tolerable workload, moderate compensation
	C	Seeing ratchety low rate motions. desired performance, tolerable workload, moderate compensation
817	A	Similar to configuration 819 but not as bad. adequate performance, tolerable workload, considerable compensation
	B	Some roll due to pitch present. Stronger pulls of pitch yielded roll-offs. Required active compensation desired performance, tolerable workload, moderate compensation
	C	Roll due to pitch is present. desired performance, tolerable workload, moderate compensation
818	A	Strong roll due to pitch observed. Controllable. Had to actively compensate for undesirable motions. adequate performance, tolerable workload, extensive compensation
	B	
	C	Roll to pitch required constant pilot compensation especially during high bank turns. desired performance, tolerable workload, moderate compensation
819	A	Heavy roll due to pitch present. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Definite roll due to pitch ...pretty noticeable! Steep angles of bank required trade-off of performance. Had to trade performance for aircraft positioning. Want to look at 2nd task. Controllable, intolerable workload, considerable compensation for control
	C	Rachety / jerky response. desired performance, tolerable workload, moderate compensation

820	A	Lots of pitch due to roll. Had to constantly back out of the loop to regain control. inadequate performance, intolerable workload, considerable compensation for control
	B	Roll due to pitch present. Real tendency for aircraft to roll over when at 60 degrees of bank. Good performance but compensation at steeper angles of bank made pilot have to back out of the loop. Controllable, intolerable workload, considerable compensation for control
	C	Roll due to pitch present. Lots of left stick required. desired performance, tolerable workload, moderate compensation
	C	Roll due to pitch present. adequate performance, tolerable workload, considerable compensation
822	A	
	B	
	C	Roll due to pitch present. High band jerky motions. adequate performance, tolerable workload, considerable compensation
823	A	Subtle dual axis coupling present that is difficult to see. Pretty good to fly. desired performance, tolerable workload, minimal compensation
	B	Can't define the cross coupling...too subtle. Minor undesirable motion present. desired performance, tolerable workload, minimal compensation
	C	desired performance, tolerable workload, minimal compensation
824	A	Mild dual axis coupling is present. Annoying pitch bobble whenever the stick is touched. desired performance, tolerable workload, moderate compensation
	B	Some minor pitch due to roll present. Minor undesirable motion present but not a problem. desired performance, tolerable workload, minimal compensation
	C	Dual axis coupling but cannot characterize them both. desired performance, tolerable workload, minimal compensation
825	A	Dual axis coupling with an annoying motion about the center stick. Worse than configuration 824. desired performance, tolerable workload, moderate compensation
	B	Roll due to Pitch present but subtle motion and barely noticeable. Desired performance, tolerable workload, minimal compensation
	C	Pitch due to roll noticeable. desired performance, tolerable workload, minimal compensation
827	A	Dual axis coupling requiring constant attention. Stick was jerky around the neutral point. Had to frequently back out of the loop. Easily induced pio. adequate performance, tolerable workload, considerable compensation
	B	Some roll due to pitch present. Some undesirable motion noticed but not easily induced and only seen during steep angles of bank. adequate performance, tolerable workload, considerable compensation
	C	Dual axis coupling. The rate is feeding the coupling and had to back out a bit. adequate performance, tolerable workload, considerable compensation
828	A	Controlable but with 'S' motions around the neutral axis. adequate performance, tolerable workload, extensive compensation
	B	
	C	Dual axis coupling observed. adequate performance, tolerable workload, extensive compensation
829	A	Needed two hands to counteract the strong undesirable motions. adequate performance, tolerable workload, extensive compensation
	B	Roll due to pitch was observed. Difficult to fly but could land it if necessary. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Roll due to pitch; control coupling. Right stab rate limiter tripped at 90 seconds into the task. inadequate performance, intolerable workload, maximum tolerable compensation
830	A	Definite dual axis coupling. Turns are unflyable. Would run out of pitch input. Right tail rate trip at 10 seconds. Uncontrollable, intolerable workload, Control will be lost during some portion of required operation
	B	Oh Wow!'. Multi-axis coupling is present and is not good. Real bad! Completely abandoned 2nd task. Terminated task for violent motions at 1 min 30 sec. not adequate performance, intolerable workload, intense compensation for control
	C	Definite level III. 80 degrees right bank observed. Safety tripped before completing task. Not controllable; control will be lost during some portion of required operation

832	A	Mild pitch due to roll; close to baseline. Minimal compensation to take care of it. desired performance, tolerable workload, minimal compensation
	B	Some undesirable motion noticeable in roll. Degree of undesirable motion was minor and annoying. desired performance, tolerable workload, moderate compensation
	C	Pitch due to roll present but minor. Borders between level 1 & 2. desired performance, tolerable workload, moderate compensation
836	A	Pitch due to roll noticeable. Undesirable motion due to rolls. adequate performance, tolerable workload, considerable compensation
	B	Pitch due to roll present but very predictable. Some oscillations occurred but only under tight control. adequate performance, tolerable workload, considerable compensation
	C	Pitch due to roll present. Sacrificing performance for compensation of cross coupling motions. Good solid level II. adequate performance, tolerable workload, considerable compensation
840	A	Controllable but a lot of bounded PIO where pilot was forced to back out of loop which drove up workload. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Significant pitch due to roll. Major deficiencies present but control was not in questions. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Lots of pitch due to roll and undesirable motions. Pilot not in the loop. Clearly a level 3 condition. inadequate performance, intolerable workload, maximum tolerable compensation
843	A	Mild roll due to pitch; close to baseline. desired performance, tolerable workload, minimal compensation
	B	Very subtle cross coupling if any. Mild oscillations in roll observed, negligible deficiencies. desired performance, tolerable workload, compensation not a factor
	C	Could not characterize the coupling. Not bad at all to fly. Trying to look for any coupling. desired performance, tolerable workload, moderate compensation
848	A	Controllable roll due to pitch. Pilot was always in the loop even though the motion was predictable. adequate performance, tolerable workload, considerable compensation
	B	Slight roll due to pitch present. Controllable. desired performance, tolerable workload, moderate compensation
	C	Roll due to pitch; every pitch input yields roll. adequate performance, tolerable workload, considerable compensation
853	A	Bad roll due to pitch; felt like rate coupling and was really jerky ('sucked'). Undesirable motions were always present and required pilot compensation. Power supply trip at end of task. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Lots of undesirable motions. Pilot was required to use larger gains to attain performance. adequate performance, tolerable workload, extensive compensation
	C	Definite roll due to pitch present. Traffic calls mid task. Felt like a filter was present (kicking motion). Had to sacrifice pitch axis performance to retain control. inadequate performance, intolerable workload, maximum tolerable compensation
854	A	Dual axis coupling but tough to see it. desired performance, tolerable workload, minimal compensation
	B	Very subtle cross coupling during rolls. Minor undesirable motions present. adequate performance, tolerable workload, minimal compensation
	C	Coupling present but so minor, could not characterize it. Clearly level 1 configuration. desired performance, tolerable workload, minimal compensation
856	A	Controllable; average level 2 aircraft. Dual axis coupling, deficiencies present but could compensate for them. adequate performance, tolerable workload, considerable compensation
	B	Not as ratchety as configuration 862 and did not produce many oscillations. adequate performance, tolerable workload, considerable compensation
	C	Lots of pitch due to roll present. Difficult to track the pitch axis; considerable compensation required. Looks like rate coupling is present. adequate performance, tolerable workload, considerable compensation

859	A	Dual axis coupling with divergent PIOs. Pilot was forced to continually stay in the loop to keep aircraft from departing. Rate monitor trip (5g's) before completion. inadequate performance, intolerable workload, intense compensation required to retain control
	B	Major cross coupling present immediately. Not controllable and was manually tripped at 5 seconds. Any slight input caused major cross coupling and sent aircraft inverted. inadequate performance, intolerable workload, intense compensation required to retain control
	C	Pitch monitor trip within 3 seconds of the task. Divergent in rate.
	C	Only able to maintain control for 13 seconds of the task. Pitch monitor tripped following large negative g unloads. Level III configuration.
861	A	Rates going on and off. Motion was easy to predict until reversals occurred. adequate performance, tolerable workload, extensive compensation
	B	Coupling had to be compensated for. Some PIO oscillations were present but only under tight control. adequate performance, tolerable workload, considerable compensation
	C	Lots of pitch due to roll that ramped up. Looked like rate coupling; lots of jumpiness. adequate performance, tolerable workload, considerable compensation
862	A	Undesirable motions not always present. Controllable. Sensitive stick. Was forced to lower gains a bit. desireable performance, tolerable workload, minimal compensation
	B	No immediately apparent cross coupling. Some pitch due to roll. No problem retaining control but required a lot of compensation. Right rate limit monitor tripped 5 seconds prior to run completion.
	C	Lots of pitch due to roll with a rapid onset. The rapid onset of pitch drove pilot out of tolerances. inadequate performance, intolerable workload, maximum tolerable compensation
863	A	
	B	Cross coupling present but less dramatic than others. Some undesirable motions occurred with tightly controlled inputs. adequate performance, tolerable workload, considerable compensation
	C	Pitch due to roll observed. Controllability not in question, better than configuration 866. inadequate performance, intolerable workload, maximum tolerable compensation
864	A	Pitch due to roll present. Moderate compensation due to oscillations during rolls. Easily induced undesirable motions. desired performance, tolerable workload, moderate compensation
	B	Pitch due to roll present with a possible washout filter. Undesireable oscillations easily induced. inadequate performance, intolerable workload, maximum tolerable compensation
	C	
865	A	
	B	Some pitch due to roll present. inadequate performance, intolerable workload, maximum tolerable compensation
	C	
866	A	
	B	Pitch due to roll was present and rolling induced lots of oscillations. Undesireable motions were present and easily induced. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Pitch to roll observed. Right rate limit monitor trip at 60 seconds into task. inadequate performance, intolerable workload, maximum tolerable compensation

867	A	Pitch due to roll present. Bounded PIO which forced pilot to back out of the loop for control. Amplitude of oscillations might be high. adequate performance, tolerable workload, extreme compensation
	B	Pitch due to roll present. Control not in question. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Pitch due to roll present and felt mostly during rolling. Feels like a level III configuration. Considerable workload to retain control. Pilot was forced to continuously back out of loop due to diverging PIOs. inadequate performance, intolerable workload, considerable compensation required for control
868	A	Right rate limit monitor trip at 5 seconds into task. VSS was rebooted
	A	Left rate limit monitor trip 15 seconds into task. Just enough of task flown to see that it's uncontrollable. uncontrollable, intolerable workload, control will be lost during some portion of required operation
	B	Pitch due to roll very noticeable. Oscillations were present and forced the pilot to become part of them. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Tail rate limit monitor trip on tail after only 3 seconds.
	C	Right and left rate limit monitor trip after only 10 seconds. Pilot only had 1/4 pitch stick control. Aircraft would takeoff in pitch axis.
869	A	Some roll due to pitch present but not immediately obvious. Saw coupling changing with longer inputs. The motions were less predictable which drove the workload up. desired performance, tolerable workload, moderate compensation
	B	Some oscillation were present but very subtle. adequate performance, tolerable workload, minimal compensation
	C	Slight pitch due to roll present. PIOs observed due to pitch bobbing with roll. Borders between a level 1 and 2 configuration. desired performance, tolerable workload, moderate compensation
870	A	Mild bobbing around the neutral position; pretty similar to configuration 869 but more annoying. Felt likt the filter wasn't doing much. desired performance, tolerable workload, moderate compensation
	B	Roll due to pitch present. Small oscillations present. Aircraft response was jerky. Minor deficiencies of oscillations induced with any longitudinal stick input. desired performance, tolerable workload, moderate compensation
	C	Filter effects are noticeable; turbulence shots and bobble annoyances. Kicks present when trying to roll. adequate performance, tolerable workload, considerable compensation
871	A	
	B	Subtle undesirable motions present. Noticed minor but annoying deficiencies. Few undesirable motions occurred under tightly controlled inputs. desired performance, tolerable workload, moderate compensation
	C	Rate coupling observed but difficult to tell if it's single or dual axis. adequate performance, tolerable workload, considerable compensation
872	A	
	B	Ratchety roll motions of larger magnitude at higher frequencies. No PIOs observed but undesirable motions were easily induced. desired performance, tolerable workload, moderate compensation
	C	Roll to pitch observed with a filter kicking in and out. Pilot learned to let the filter do it's thing then control as needed. desired performance, tolerable workload, moderate compensation
873	A	Rolling motions present when trying to pitch. Oscillations were present. Maybe a filter present? CHR of a 3 or 4; requested a refly.
	A	After this refly: desired performance, tolerable workload, moderate compensation
	B	
	C	Roll due to pitch present with some rate coupling observed. adequate performance, tolerable workload, considerable compensation
874	A	
	B	Roll due to pitch present with ratchety motion in roll axis. Unpleasant motions but tolerable and able to focus on the task. Lots of undesirable motions present easily induced with light stick forces. desired performance, tolerable workload, moderate compensation
	C	

875	A	Roll due to pitch present. Really bad bizare motions. Changed configuration went into BIT. Very tough to fly with divergent PIOs and rachety rolling motions. After two violent side motions, safety pilot manually triped the VSS to end the task. inadequate performance, intolerable workload, intense compensation required to retain control
	B	Pitch due to roll present with a washout filter. Lots of oscillations. Saw some bounded PIO. Inputs on stick would jerk back on the pilot. adequate performance, tolerable workload, extensive compensation
	C	Looks like level II configuration of rate coupling with filter. Aircraft response is jerky but able to fly. Roll commands are noticeable; maybe dual axis couplling. adequate performance, tolerable workload, considerable compensation
876	A	Really strong side motions. Compensation was driven by the need to lower gain to control the nasty motions. No PIOs but easily induced undesirable motions. adequate performance, tolerable workload, considerable compensation
	B	Unsure of type of cross coupling present. Very jerky motions observed. Would like to look at secondary task performance. Bounded PIOs observed. adequate performance, tolerable workload, extensive compensation
	C	Lots of roll due to pitch observed with a fast filter. Had to reduce gains in pitch for performance. adequate performance, tolerable workload, considerable compensation
877	A	
	B	Roll due to pitch observed with low frequency washout. Rolly motion was present. Saw PIOs start to diverge throughout task. adequate performance, tolerable workload, extensive compensation
	C	On the line between a level II and III configuration. Workload drove the rating. Really had to back out of the loop on gains. adequate performance, tolerable workload, extensive compensation
878	A	
	B	Lots of rachety motion in roll axis. Lots of oscillations. Rolliness was very objectionable. adequate performance, tolerable workload, cextensive compensation
	C	
879	A	Tendency for bounded PIOs. Extensive compensation required for jerkiness around neutral point. Possible rate coupling with filter? adequate performance, tolerable workload, extensive compensation
	B	Ratchety in roll; bumpy motions left and right. Would like to look at stick inputs. Did not see PIOs but undesirable motions easily induced. adequate performance, tolerable workload, considerable compensation
	C	Perhaps dual axis coupling. Compensation required was low gain control and it felt that high gain would cause diverging PIOs. inadequate performance, intolerable workload, maximum tolerable compensation
880	A	Nasty oscillations were present. Possibility of a filter? Diverging PIOs observed. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Similar to configuration 878; ratchety in roll and magnitude of motions were more noticeable. Bounded PIO was experienced which required pilot to back out of the loop. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Required to reduce gains to prevent PIOs. Lots of backing out of the loop required. Looks like rate coupling. inadequate performance, intolerable workload, maximum tolerable compensation
881	A	
	B	Pitch to roll present with lots of oscillations observed. Definite bounded PIO tendency. inadequate performance, intolerable workload, maximum tolerable compensation
	C	
882	A	
	B	Lots of pitch due to roll. Sensitive configuration. Many oscillations present with low gain inputs. inadequate performance, intolerable workload, maximum tolerable compensation
	C	Pitch due to roll observed with rate filtering. Motions would build and spike; strong level III configuration. inadequate performance, intolerable workload, considerable compensation required for control

883	A	Motions get worse when pilot gets in the loop. There was some filtering going on. adequate performance, tolerable workload, considerable compensation
	B	Pitch due to roll observed and lots of oscillations present. Divergent PIO observed. inadequate performance, intolerable workload, considerable compensation required for control
	C	Lots of pitch due to roll present. Rate coupling observed. Roll caused PIO in pitch which forced reduced gains to retain control. Definite level III configuration. inadequate performance, intolerable workload, intense compensation required for control
884	A	Unpredictable pitch during rolls. Couldn't land this airplane; tough to fly. Barely controllable. inadequate performance, intolerable workload, maximum tolerable compensation
	B	Many oscillations. Definite PIO tendency. Pilot was forced to reduce gain not to experience divergent PIOs. inadequate performance, intolerable workload, considerable compensation required for control
	C	Lots of pitch due to roll. Rate coupling present. Had to significantly reduce gains to avoid tendency to diverge in the roll axis. inadequate performance, intolerable workload, intense compensation to retain control
886	A	Little bit of 'push' stick pressure to compensate for slight undesirable motions. desired performance, tolerable workload, minimal compensation
	B	Aircraft wanted to nose up. Minor undesirable motions. desired performance, tolerable workload, minimal compensation
	C	Did not notice coupling. Constant bias present. desired performance, tolerable workload, moderate compensation
888	A	Roll rate was present but milder than previously seen. 2-3 lbs of left stick force required. desired performance, tolerable workload, minimal compensation
	B	Bias was not abrupt and no cross coupling observed. Constant right stick was required to counter the left roll bias. desired performance, tolerable workload, minimal compensation
	C	Angle of attack trip at over 1 minute into the task. Constant roll bias and did not see coupling. Compensation was stick input. adequate performance, tolerable workload, considerable compensation
890	A	Controllable. Compensation was minimal once the pitch rate identified. 5 lbs of constant back pressure was required. desired performance, tolerable workload, minimal compensation
	B	No cross coupling noticeable. Needed a little nose-up trim. No undesirable motions observed. adequate performance, tolerable workload, minimal compensation
	C	Couldn't release stick without seeing bias. The pitch bias was easier to compensate for than the roll bias. Overall, not too bad. desired performance, tolerable workload, moderate compensation
	C	Tracking was rock solid and felt like a level I configuration. Did not notice much undesirable motion. desired performance, tolerable workload, minimal compensation
892	A	No undesirable motions detected. The roll rate bias was driving the required inputs for compensation. desired performance, tolerable workload, minimal compensation
	B	No cross coupling noticeable. No undesirable motions observed. adequate performance, tolerable workload, minimal compensation
	C	Similar to baseline, could not detect coupling. desired performance, tolerable workload, minimal compensation
	C	Compensation was moderate due to the bias. Rolling motion was undesirable and no coupling detected. desired performance, tolerable workload, moderate compensation

APPENDIX F: FULL PAGE PLOTS

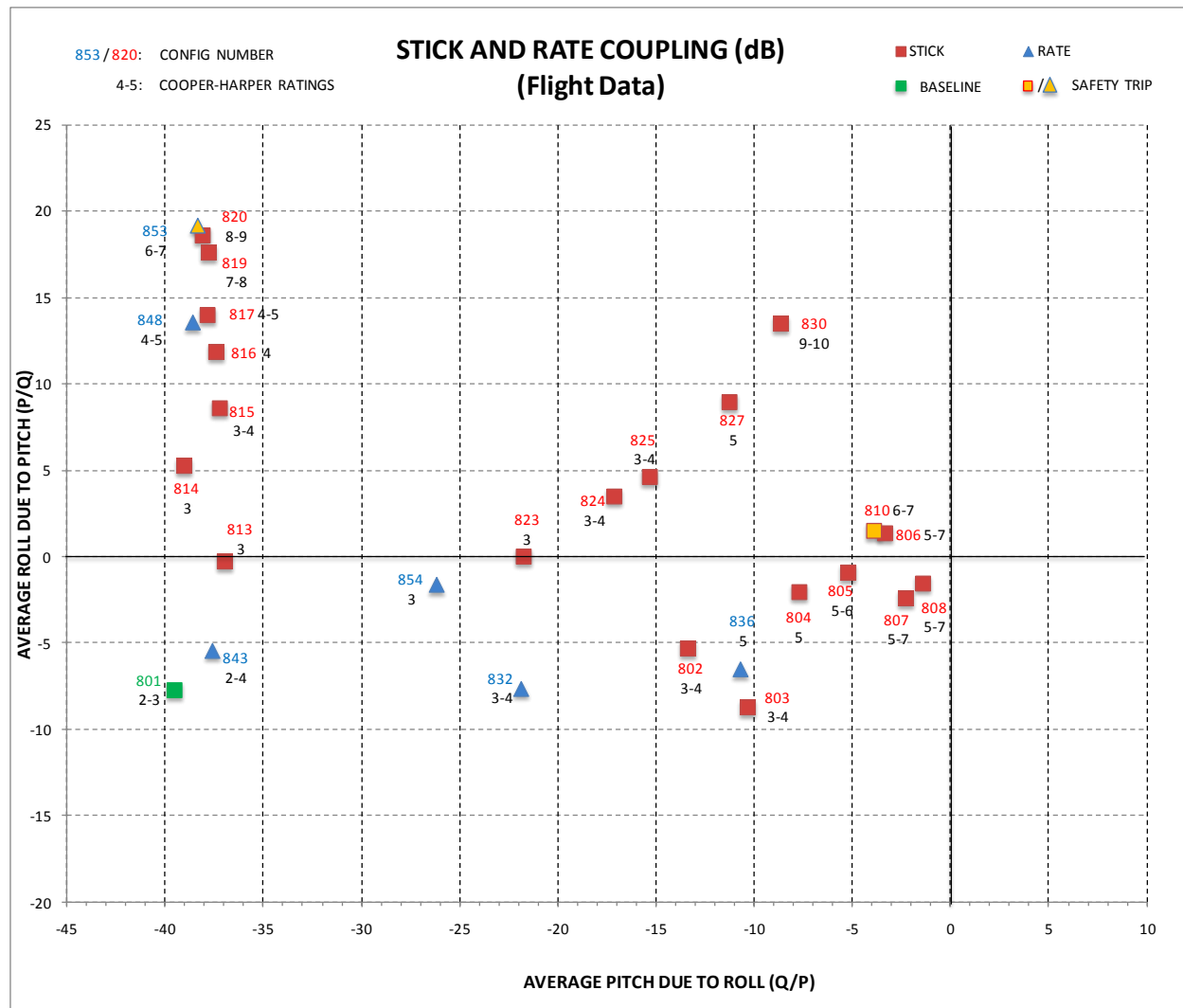


Figure F-1: Stick and Rate Coupling (dB) – Flight Data

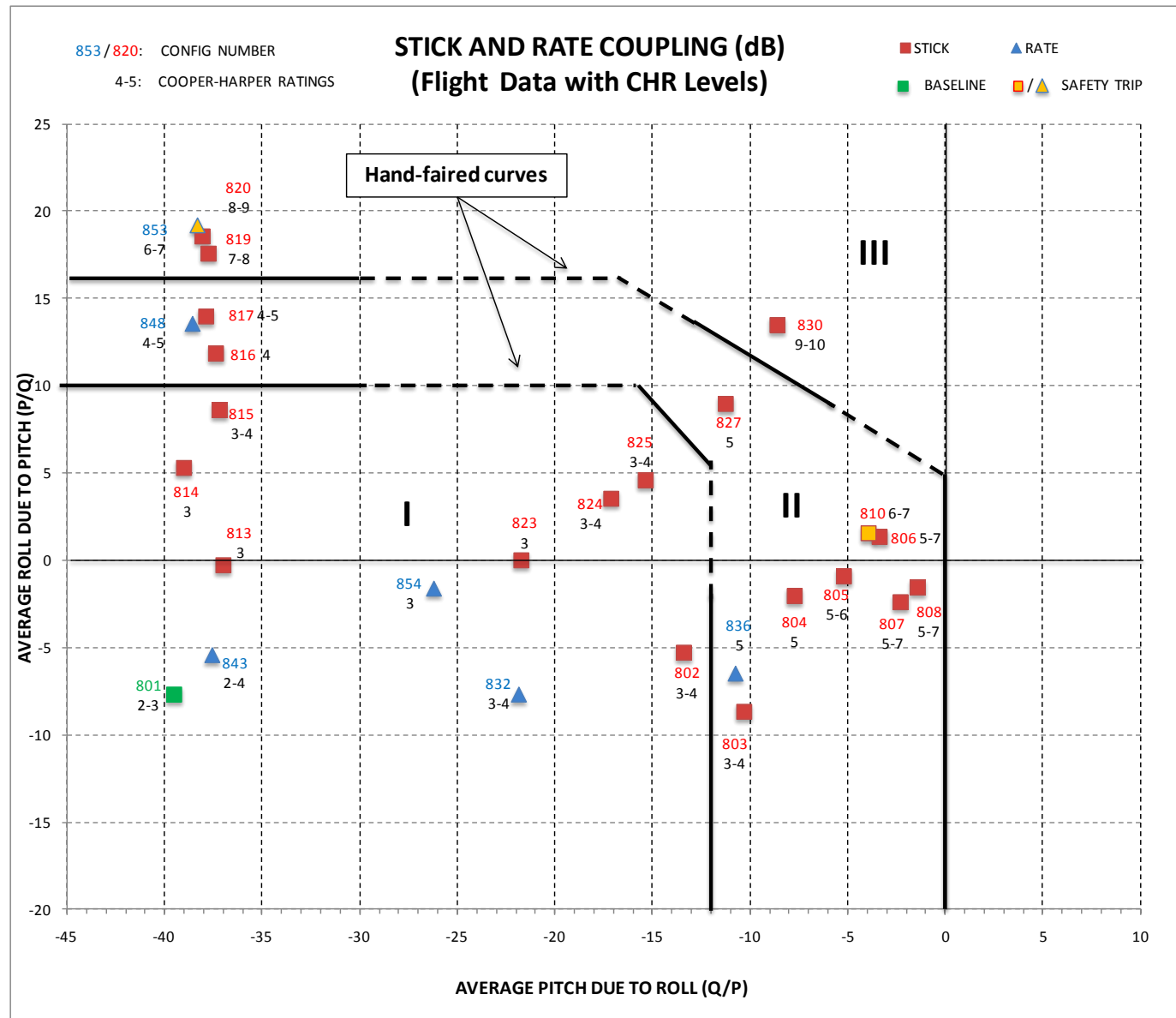


Figure F-2: Stick and Rate Coupling (dB) – Flight Data with CHR Levels

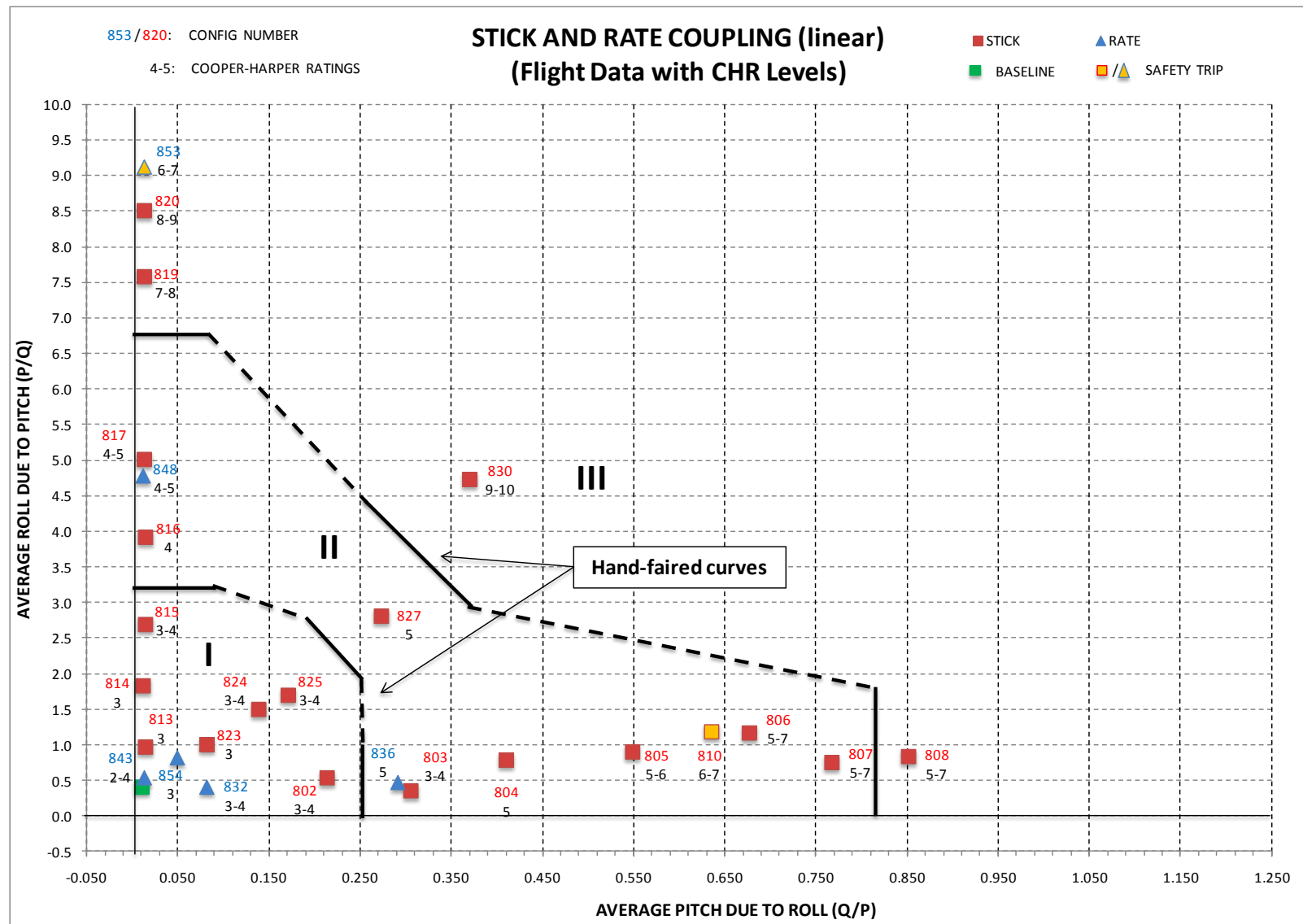


Figure F-3: Stick and Rate Coupling (linear) – Flight Data with CHR Levels

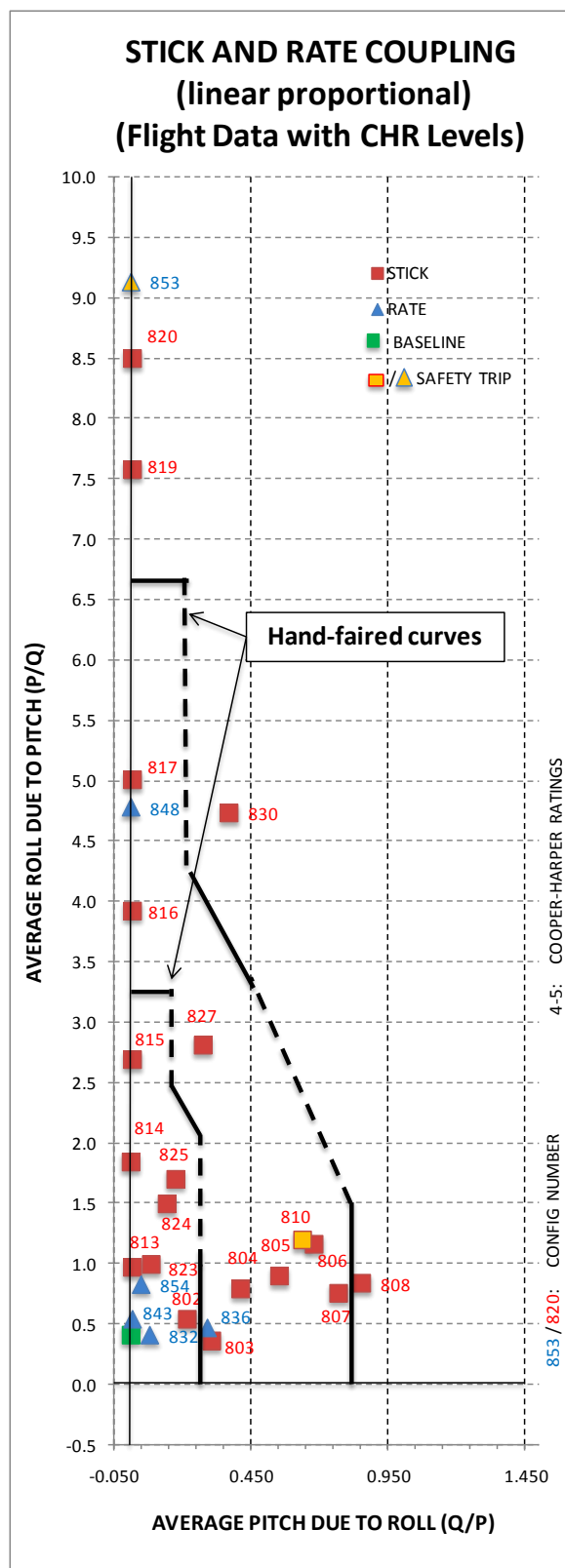


Figure F-4: Stick and Rate Coupling (linear proportional) – Flight Data with CHR Levels

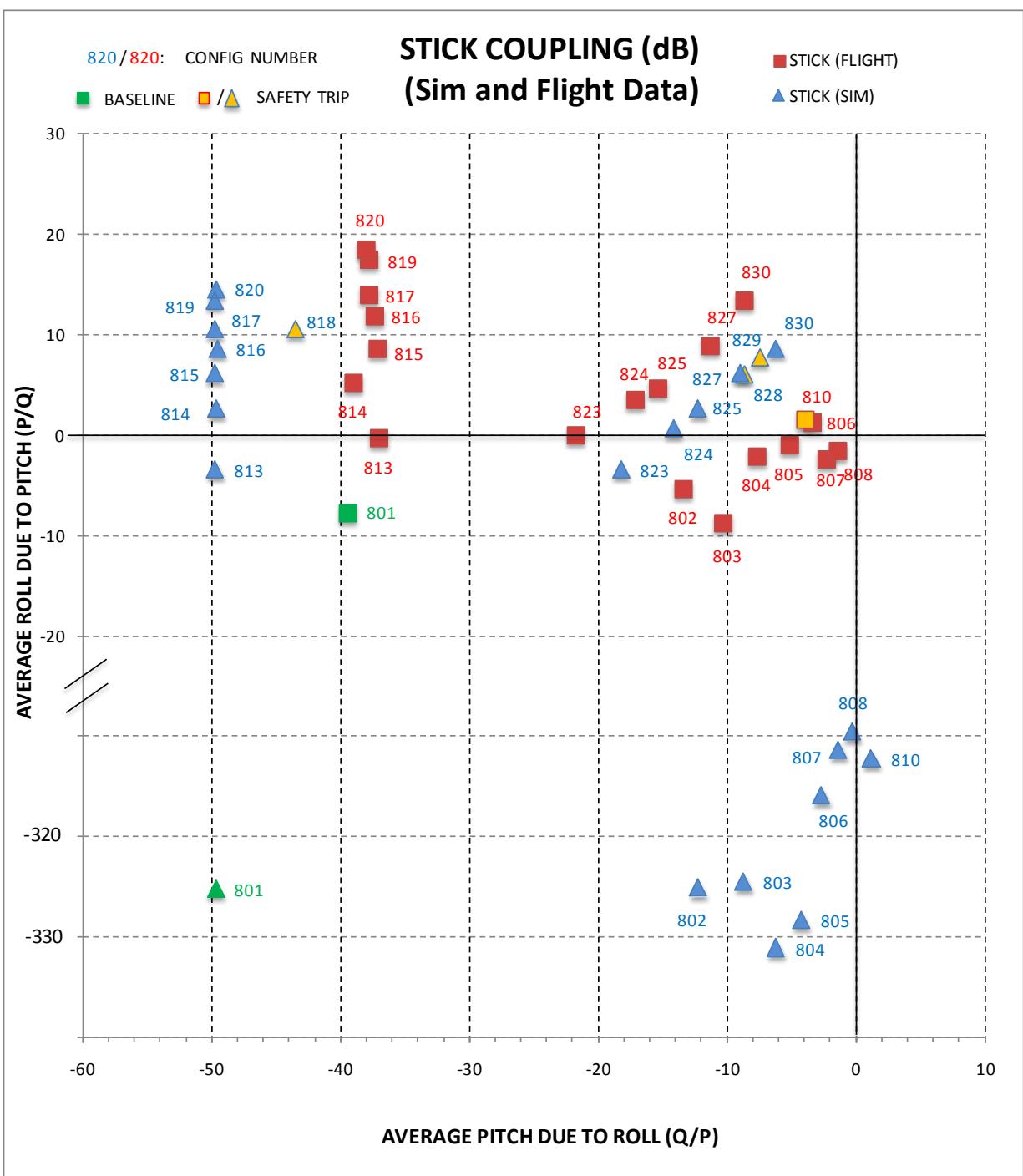


Figure F-5: Stick Coupling (dB) – Sim and Flight Data

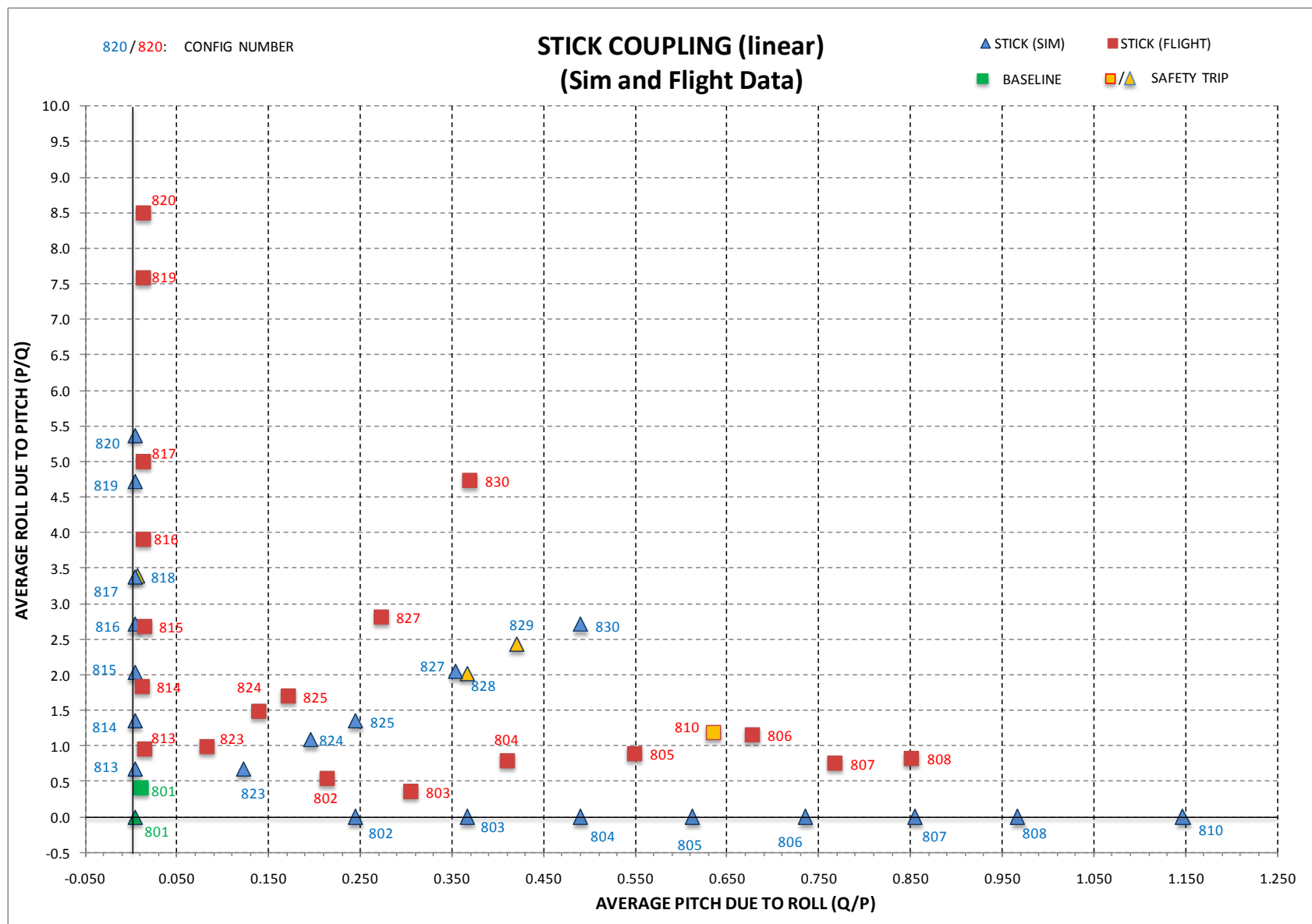


Figure F-6: Stick Coupling (linear) – Sim and Flight Data

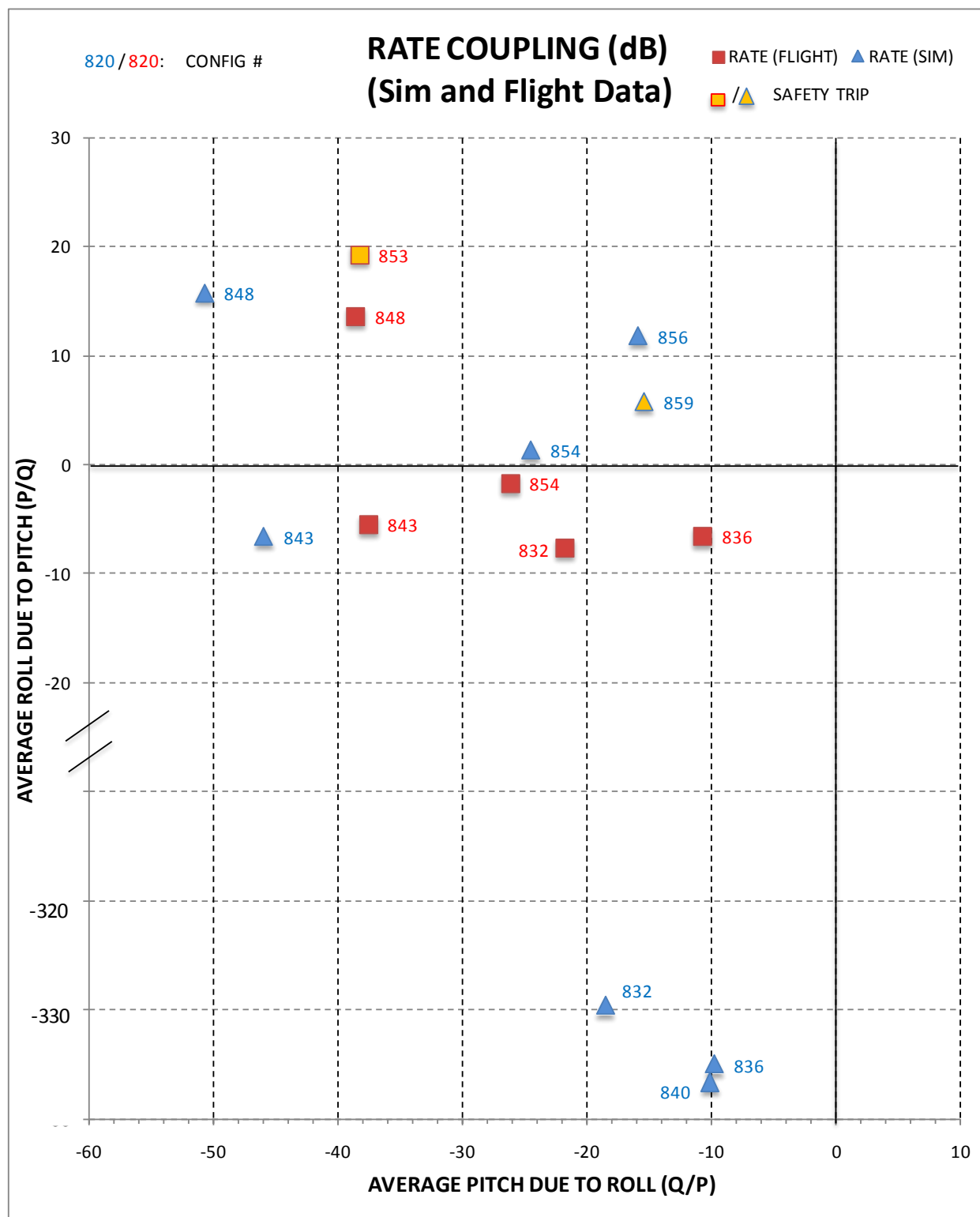


Figure F-7: Rate Coupling (dB) – Sim and Flight Data

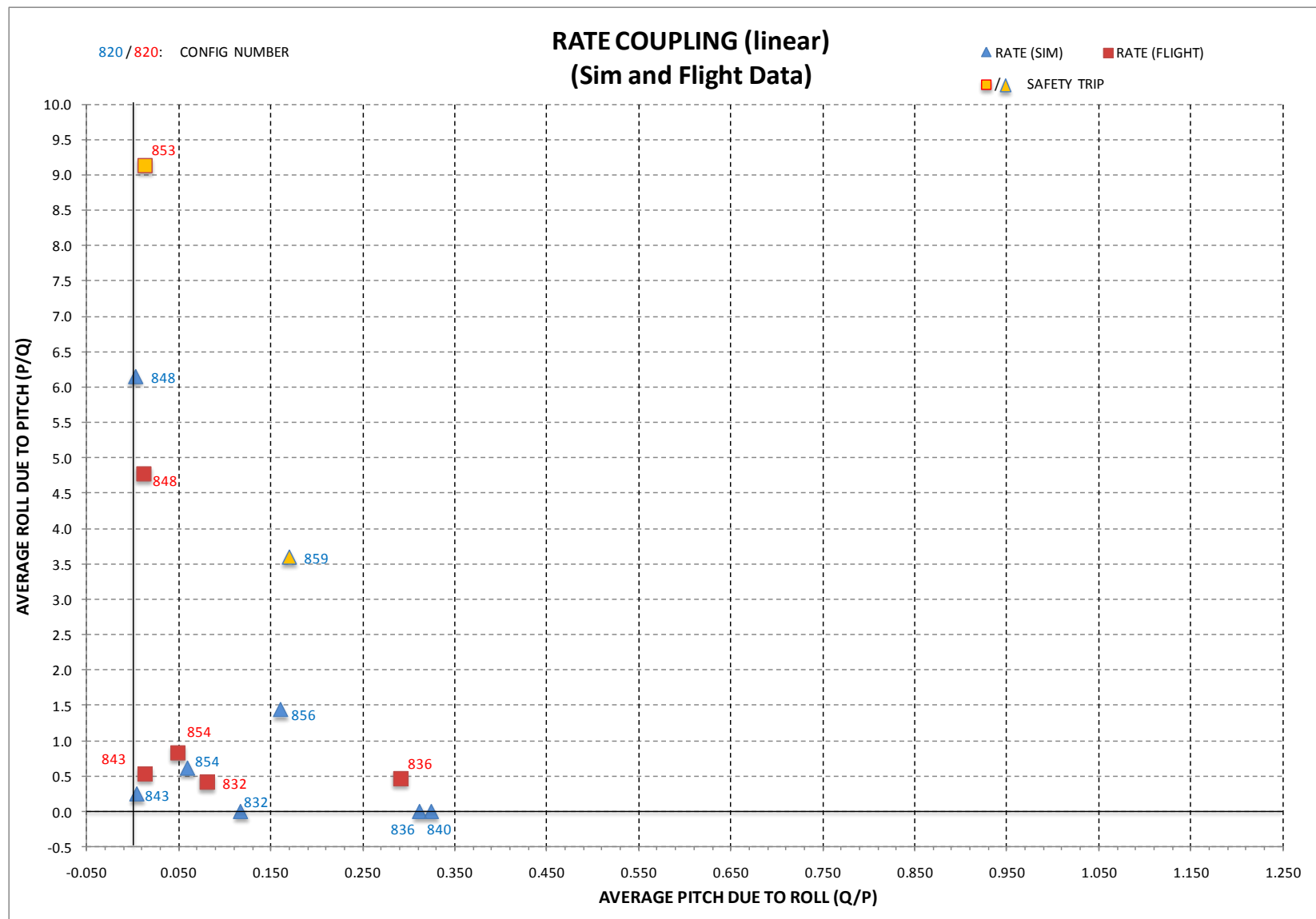


Figure F-8: Rate Coupling (linear) – Sim and Flight Data

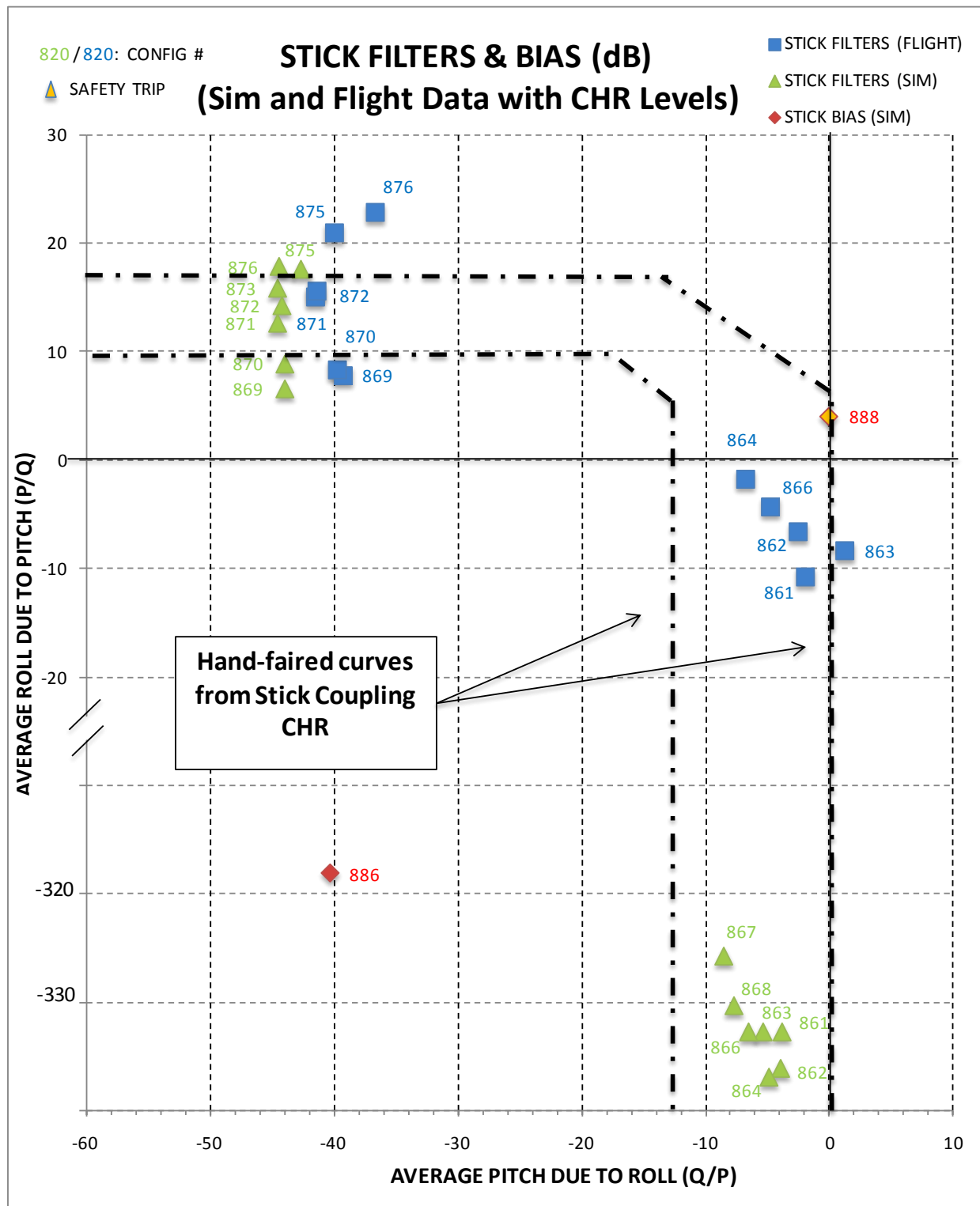


Figure F-9: Stick Filters and Bias (dB) – Sim and Flight Data with CHR Levels

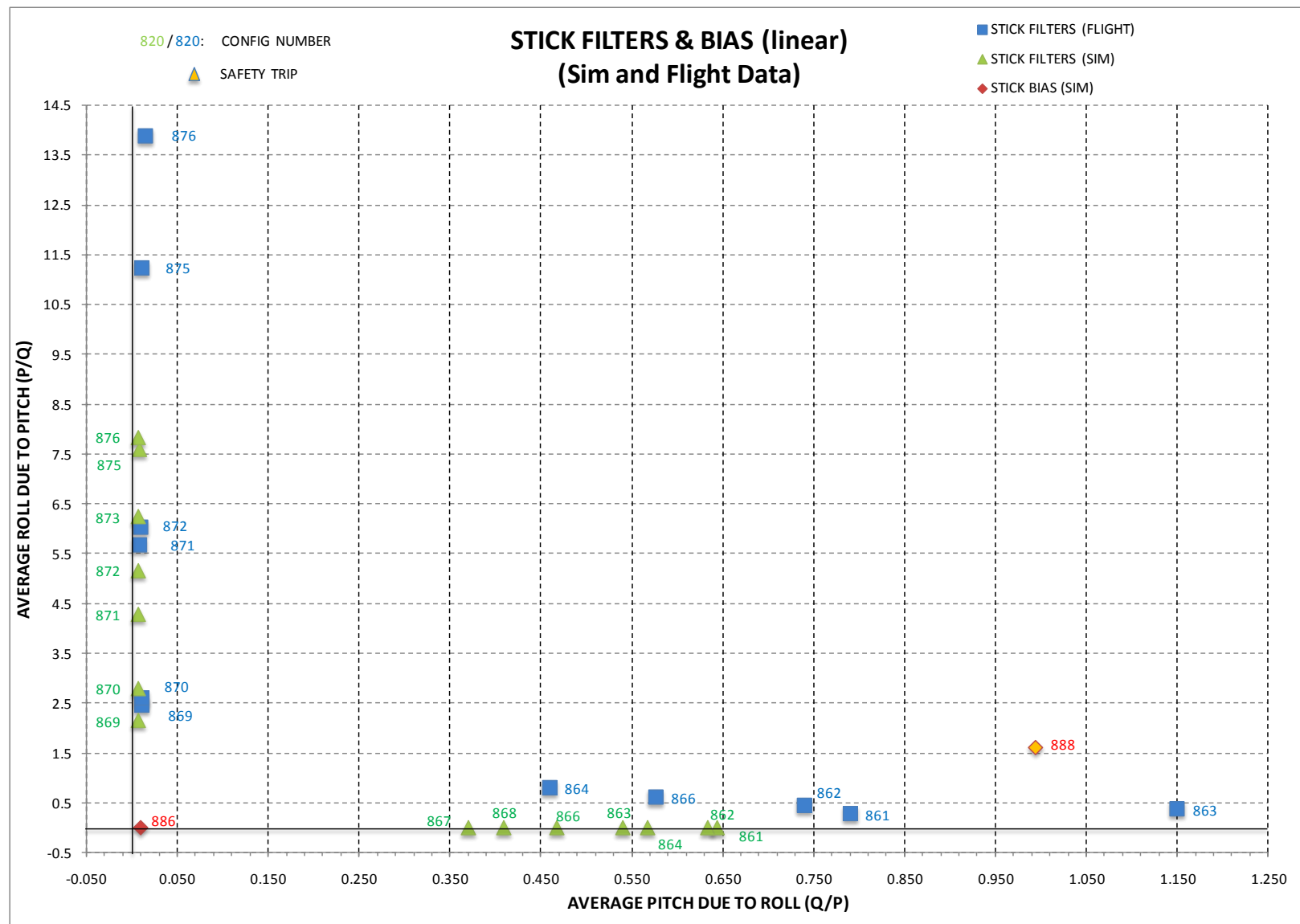


Figure F-10: Stick Filters and Bias (linear) – Sim and Flight Data

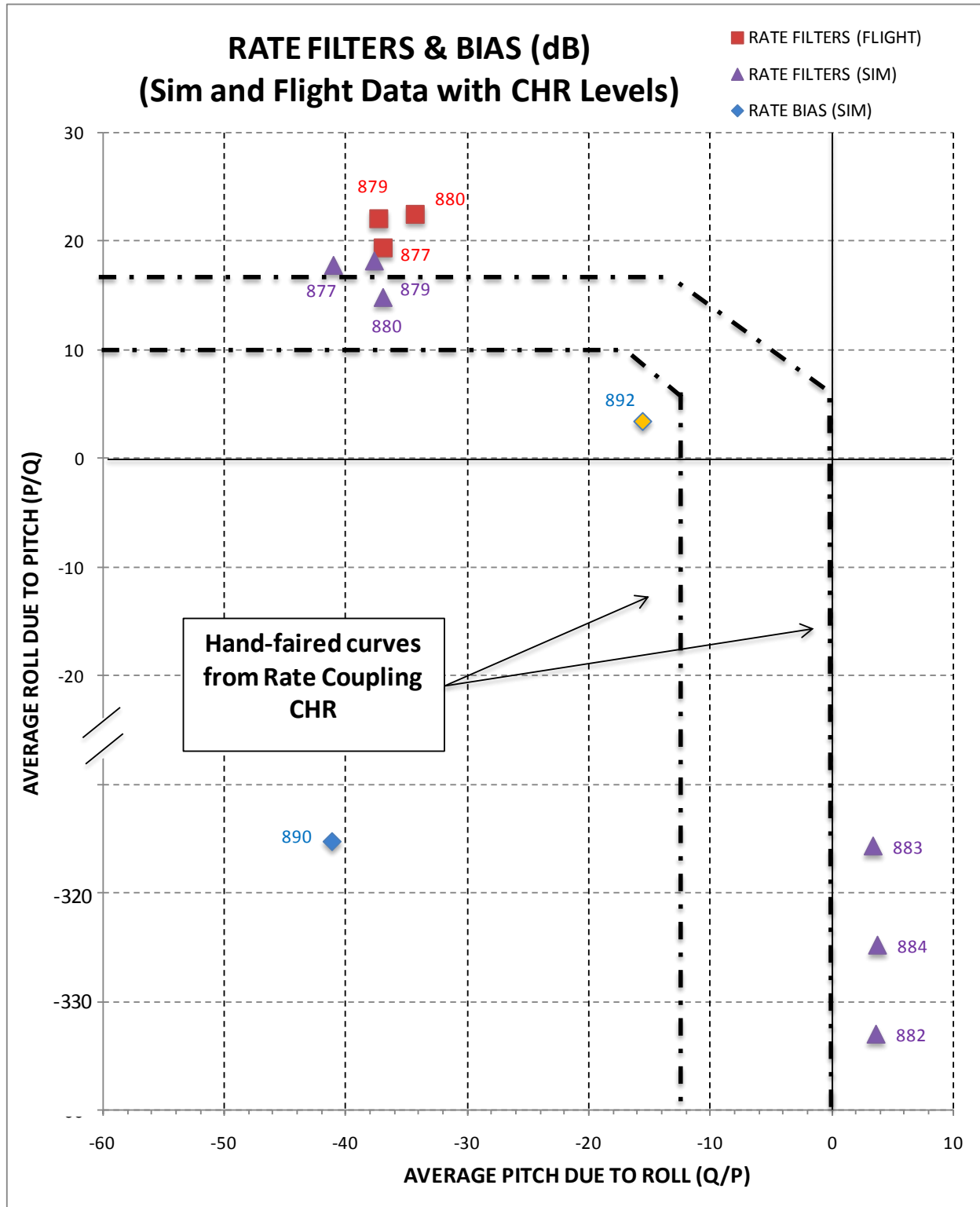


Figure F-11: Rate Filters and Bias (dB) – Sim and Flight Data with CHR Levels

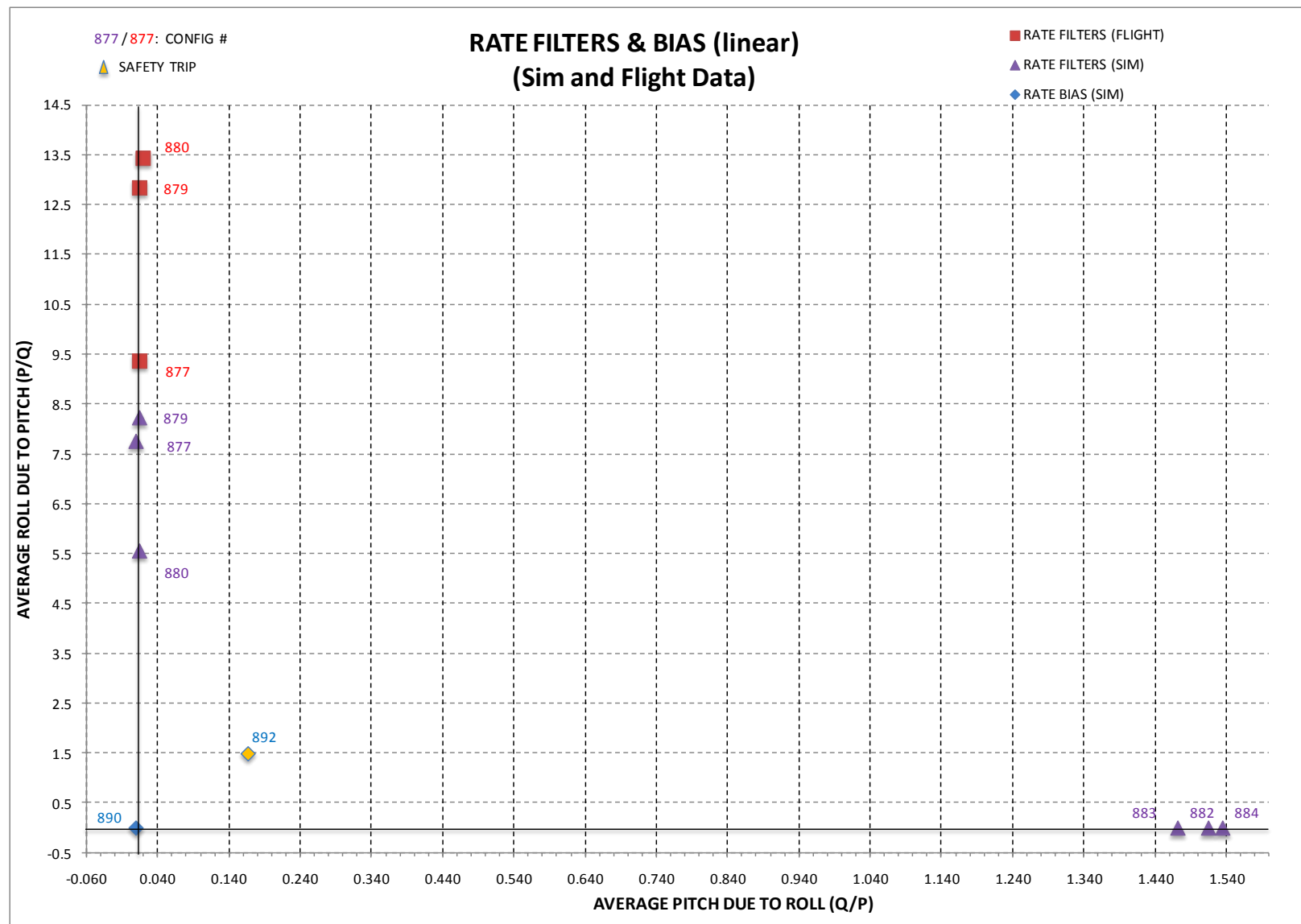


Figure F-12: Rate Filters and Bias (linear) – Sim and Flight Data

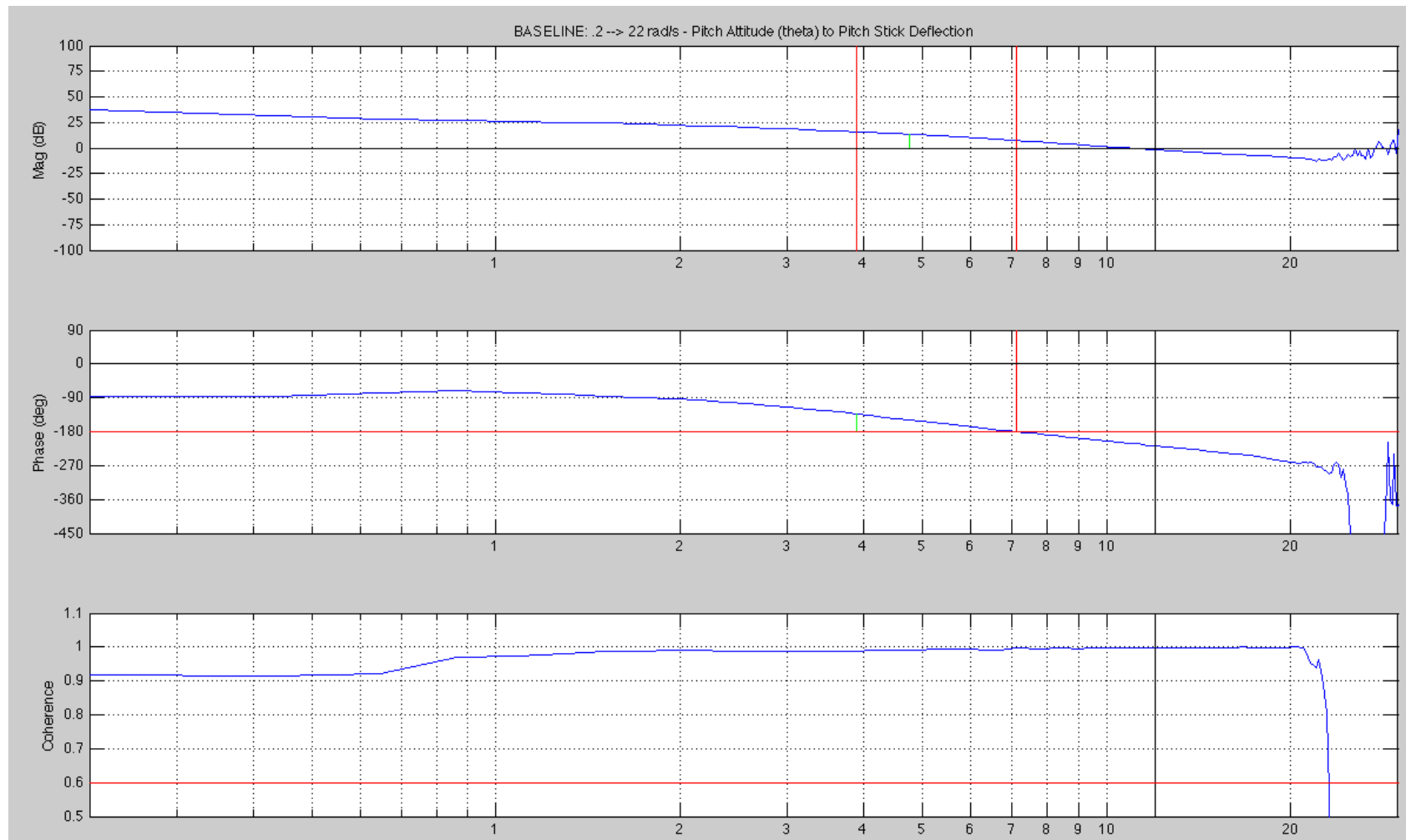


Figure F-13: Baseline Pitch Axis Bode Plot

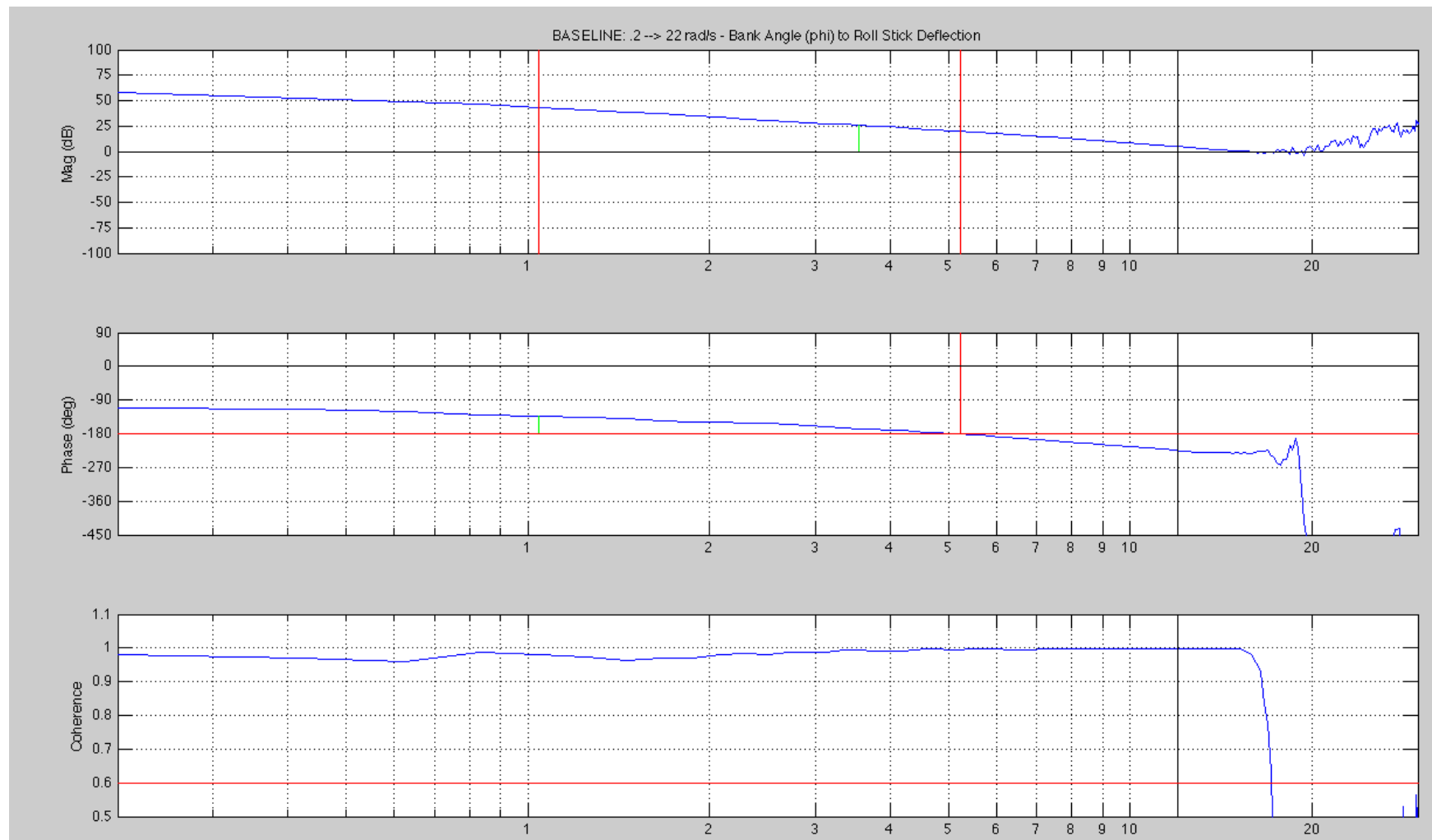


Figure F-14: Baseline Roll Axis Bode Plot

APPENDIX G: FLIGHT LOGS

Table G-1. Summary of Flights

Flight Number	Type of Flight	Date	Evaluation Pilot/Engineer	Sortie Duration
01	Flying Qualities	8 MAR 10	Engineer: Capt Jade Lemery	1.6
02	Flying Qualities	10 MAR 10	Engineer: Capt Robert Koo	1.0
03	Handling Qualities	11 MAR 10	Pilot: Maj Dail Fields	1.7
04	Flying Qualities	12 MAR 10	Engineer: Capt Katie Ryan	1.6
05	Handling Qualities	12 MAR 10	Pilot: Maj David Marten	1.7
06	Handling Qualities	15 MAR 10	Pilot: Capt Gianmarco Di Loreto	1.4
07	Handling Qualities	16 MAR 10	Pilot: Capt Gianmarco Di Loreto	1.4
08	Handling Qualities	25 MAR 10	Pilot: Maj David Marten	1.7
09	Handling Qualities	26 MAR 10	Pilot: Maj Dail Fields	1.9
10	Handling Qualities	27 MAR 10	Pilot: Maj Dail Fields	1.7
11	Handling Qualities	27 MAR 10	Pilot: Maj David Marten	1.7
12	Flying Qualities	29 MAR 10	Engineer: Capt Jade Lemery	1.7
13	Handling Qualities	29 MAR 10	Pilot: Capt Gianmarco Di Loreto	1.9
TOTAL				21.0

Table G-2. Flight Log of Configurations Flown

Run #	Flight 01	Flight 02	Flight 03	Flight 04	Flight 05	Flight 06	Flight 07	Flight 08	Flight 09	Flight 10	Flight 11	Flight 12	Flight 13
01	801	832	801	832	801	801	801	801	801	801	801	801	801
02	802	836	803	836	813	813	832	832	854	864	876	810	884
03	803	840	803	840	815	803	854	854	832	878	880	820	890
04	804	843	813		803	824	836	856	888	880	801	805	827
05	805	848	815		824	815	843	870	862	881	892	816	879
06	806	853	824		819	825	808	869	856	874	888	830	862
07	807	854	804		817	804	840	853	892	828	811	840	883
08	808	856	819		804	819	869	848	869	866	818	853	892
09	810	859	817		805	817	870	840	853	882	890	861	876
10	813	861	805		830	805	816	801	848	879	884	868	888
11	814	862	830		830	830	868	859	840	871	879	875	886
12	815	867	825		825	801	801	836	801	801	886	876	801
13	816	868	801		801	823	875	861	859	877	801	811	807
14	817	869	820		802	806	848	875	861	863	883	863	880
15	819	870	802		823	820	814	862	870	872	872	864	861
16	820	875	823		820	802	853	843	836	884	829	865	828
17	823	876	806		806	810	859	868	875	829	828	866	864
18	824	879	810		810		867	867	868	865	871	871	864
19	825	880	814		808		856	888	867	809	877	872	873
20	826	883	807		816			886	843	828	882	873	873
21	827		808		814			859	890		873	874	829
22	830		816		807			892	886		866	877	829
23					827			868	876		863	878	818
24					801			890	883				
25					820								

Configurations were flown in the order shown.

APPENDIX H: PILOT EXPERIENCE

Table H-1. Pilot Experience

	Pilot Experience
Pilot A	Fighter aircraft background with experience in the Tornado and test experience in the Italian Air Force
Pilot B	Fighter aircraft background with 1260 hours of flight time in the F/A-18 A-F
Pilot C	Bomber aircraft background with 1700 total hours of flight experience in the B-1 Bomber

This page was intentionally left blank.

APPENDIX I: FLYING QUALITIES FLIGHT SUMMARIES

Flying qualities test flight procedures were conducted as follows: the safety pilot stabilized the aircraft at 15,000 ft PA, 1g, and 300 KCAS. The desired test configuration was selected from the aft cockpit and the setup parameters (pitch and roll initial attitudes) established for each PTI. From the front cockpit, the center stick was selected and throttles were matched. The backseat pilot would then engage the VSS and once engaged, the PTI was initiated in the front seat on the right MFD by selecting push button 16. Controls were released and aircraft was monitored during the PTI. The record number, configuration, and pilot/FTE comments were passed to the control room prior to selecting the next PTI. The pitch and roll PTIs were completed from 0.2 to 22 rad/sec for the baseline configuration and 0.2 to 12 rad/sec for cross-coupled configurations. Each PTI was programmed for a 30 second time period with an equal dwell time at each frequency (power equal to one).

Flying Qualities Flight 1

During this flight, pitch and roll frequency sweep PTIs for the baseline and each stick coupled configuration were conducted. The pitch frequency for the baseline configuration resulted in a VSS safety trip due to rate limit of the elevator control surface at the higher end of the frequency range. The roll frequency sweep was successfully completed. Configuration 802 produced some “noticeable cross-coupling” during the roll frequency sweep PTI, but no safety trips. The pitch PTI for configuration 803 produced a slow right roll during the PTI which resulted in a 70 degree right angle of bank at the completion of the PTI. This right roll was not expected because the pitch PTI was intended to only input longitudinal surface movements and the configuration was not intended to have any roll due to pitch. After some discussion, the control room recommended that the FTE maintain as close to wings level as possible (<15 degrees angle of bank) with lateral input as needed during the PTI. This approach was used for remaining pitch PTIs for single-axis coupling configurations with pitch due to roll (804-810). Configurations 805-810 produced safety trips during the roll PTI at frequencies that decreased as cross-coupling values increased (25 sec trip for 806, 15 sec trip for 810). The safety pilot and FTE noted that the initial setup of 10 degrees nose high was not required for the pitch due to roll single-axis control coupling configurations.

Flying Qualities Flight 2

Due to the observed roll tendency of the VISTA with VSS engaged in the baseline configuration the beginning of this flight was spent investigating this issue further. Trim shots were performed at 300 KCAS in the baseline configuration (801). Next, two manual and two PTI frequency sweeps were performed in order to gather characterization data for the VISTA baseline. Additionally, frequency sweep PTIs were performed for two rate coupling test configurations (832 and 836). Analysis of the VISTA baseline configuration revealed significant coupling was inherently present and is discussed in the results and analysis section below.

Flying Qualities Flight 3

This sortie consisted of PTI frequency sweeps for nine rate coupling configurations including both pitch due to roll and roll due to pitch as well as two-axis coupling. The VSS tripped on configuration 840 (high pitch due to roll) and configuration 856 (two-axis rate coupling) was intentionally terminated once the aircraft went inverted throughout the sweep. Configuration 859 (high gain two-axis rate coupling) was also terminated by the safety pilot as the pitch and roll rates rapidly accelerated toward the safety trip limits. This type of aircraft response was expected during these configurations. Next, pitch and roll frequency sweeps were performed for 11 rate filtered configurations. Some VSS trips were encountered but overall, these points were more flyable than expected.

Flying Qualities Flight 4

A fourth and final flying qualities flight was flown to complete open-loop characterizations of the remaining test points (planned and backup). Additional time was available in the sortie to allow the FTE to perform a combination of manually-flown raps, doublets and frequency sweeps for some of the configurations that had previously tripped the VSS when using the PTI. Manual frequency sweep data were used during the analysis, where needed, to augment PTI data. A total of 23 configurations were flown on this flight.

APPENDIX J: ICARUS SOFTWARE DIAGRAMS

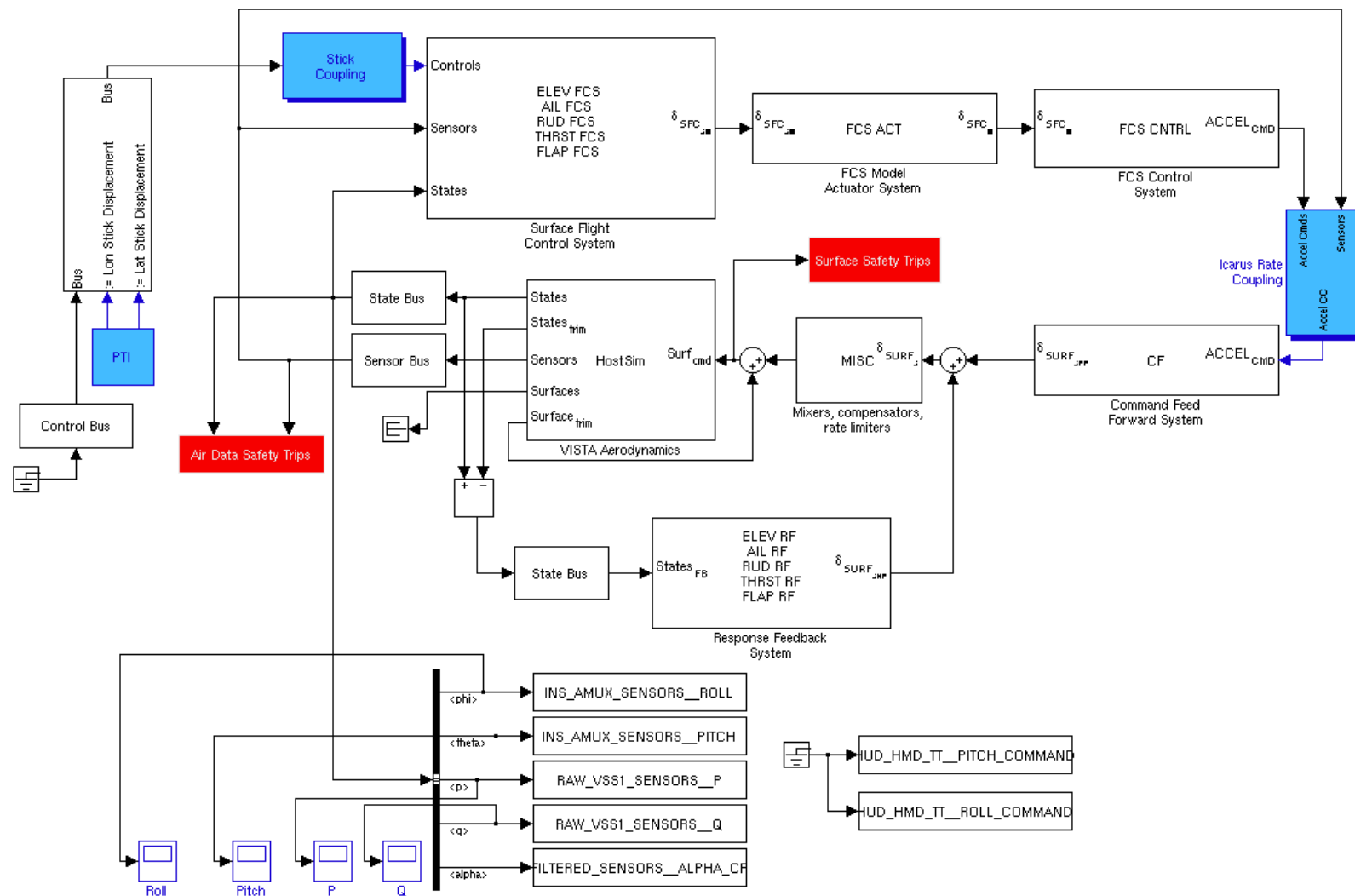


Figure J-1. Top-Level Icarus Software on Simulator

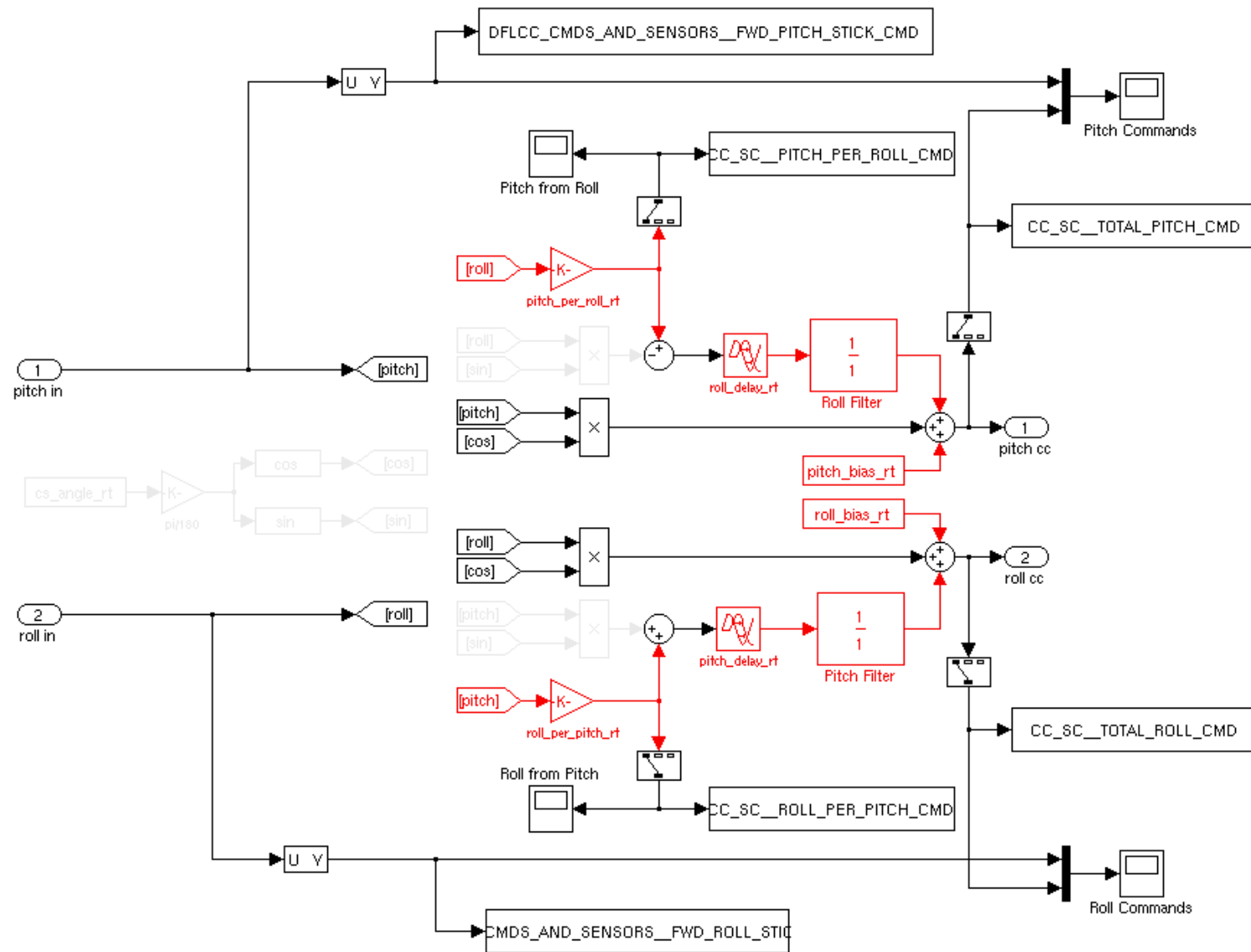


Figure J-2. Icarus Stick Coupling Block

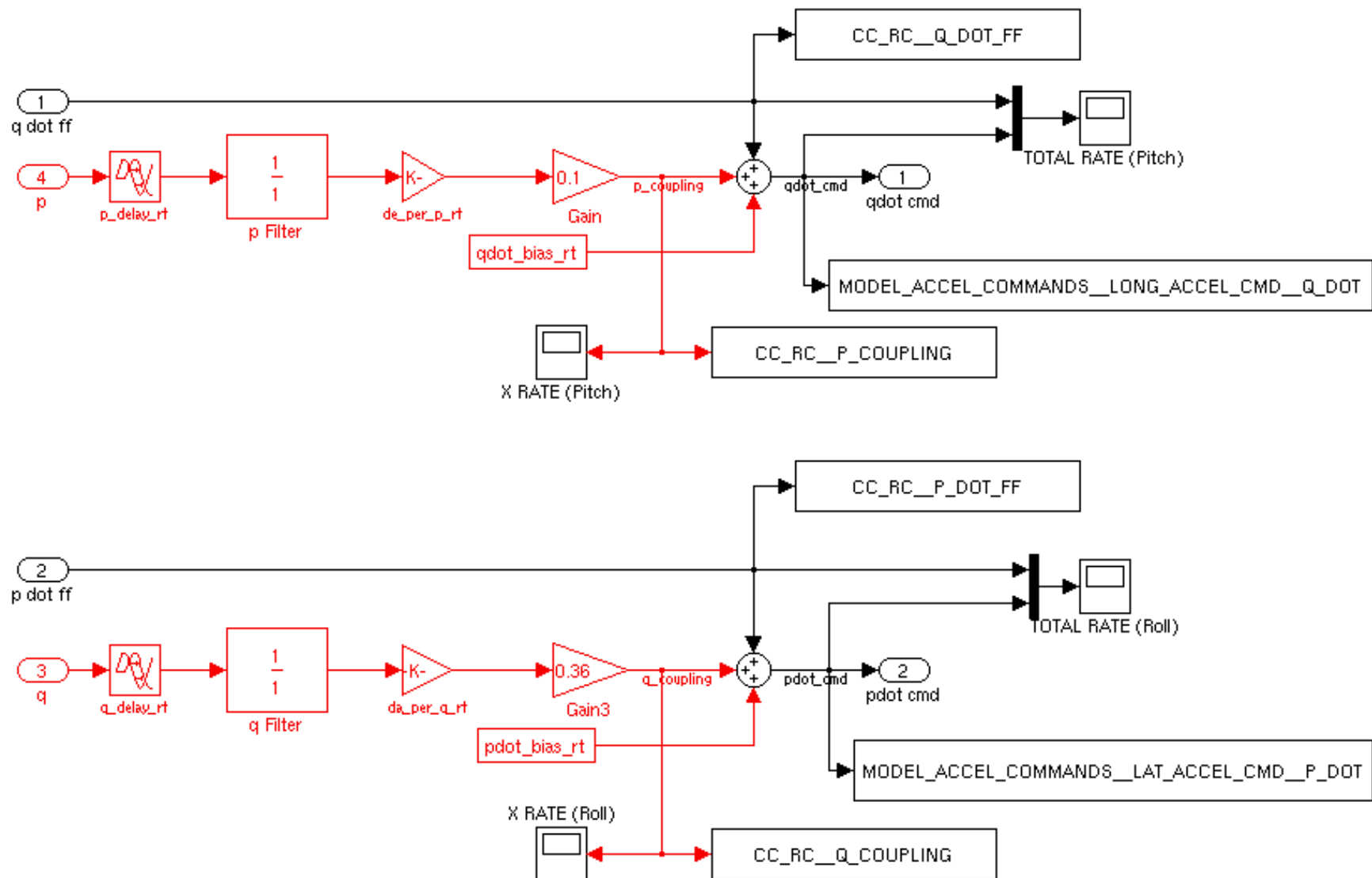


Figure J-3. Icarus Rate Coupling Block

This page was intentionally left blank.

APPENDIX K: CONFIGURATION 000 DESCRIPTION

Configuration 000 is a configuration of the VISTA Simulation System (VSS) designed for use from 15,000 to 20,000 feet pressure altitude and 250 to 350 knots. It incorporates safety trips “designed to manually or automatically disengage the VSS when a failure occurs or a VSS aircraft limit is exceeded. The VSS aircraft limits define an envelope within the normal F-16 operating envelope. If a disengagement occurs, the subsequent transients should stay within this normal F-16 envelope.” (reference 7)

There are seven general classes of safety trips in the VISTA; the limits listed below are one type relevant to this test and are called VISTA Integrity Monitor (VIM) limits. “VIM safety trips are designed to provide failsafe protection for VISTA regardless of failures to the VSS. To accomplish this, VIM monitors the aircraft state and the status and operation of the VSS to detect and recover from system failures or hazardous conditions.” (reference 7)

VIM Limits

Maximum angle of attack = 16.00 degrees

Minimum angle of attack = -10.00 degrees

Maximum vertical acceleration N_z = 6.80g

Minimum vertical acceleration N_z = -2.40g

Maximum angle of sideslip = 10.00 degrees

Maximum elevator monitor value = 8.00g

Minimum elevator monitor value = -5.00g

Maximum aileron monitor value = 300.00 degrees/second

Maximum rudder monitor value = 30.00 degrees/second

Flaperon/ASE/hardover/rate limit trips enabled for cruise configuration

Rate limit trips encountered during test flights included:

VIM: RF_RATE_LIM_MON Right flaperon command exceeds 70 deg/sec for 500 msec.

VIM: LF_RATE_LIM_MON Left flaperon command exceeds 70 deg/sec for 500 msec.

VIM: RT_RATE_LIM_MON Right horizontal tail command exceeds 70 deg/sec for 115 msec.

VIM: LT_RATE_LIM_MON Left horizontal tail command exceeds 70 deg/sec for 115 msec.

VIM: PITCH_MON Pitch command exceeded the maximum allowable during VSS operation.

For more information concerning Configuration 000, please contact Calspan Corporation.

This page was intentionally left blank.

APPENDIX L: SIGNAL FILTERING

The following information is duplicated from reference 7, a memorandum from Mr. Dave Mitchell titled Washout Filter Designs.

BACKGROUND

In a highly-augmented aircraft, the impact on handling qualities due to loss of a primary control effector is likely to be minimized through artificial augmentation and adaptation. The application of a control effector for multiple purposes may introduce unusual and nonlinear response dynamics in the primary and coupled axes. Because this test program is the first to examine the effect of cross-coupling on handling qualities for a fixed-wing airplane, most of the configurations were implemented as simple stick crossfeeds. A subset was designed to provide an initial investigation of the effect of higher-order dynamics, such as those that would be encountered in an actual highly-augmented aircraft.

Many dynamic forms for the cross-coupled response could be defined. As a starting point, it was assumed that the out-of-axis response would be in the form of a washout circuit – an initial large command to the cross-coupled effector to initiate the desired response, followed by a rapid removal of the command so that the effector is returned to trim.

SELECTION OF FILTER DESIGN

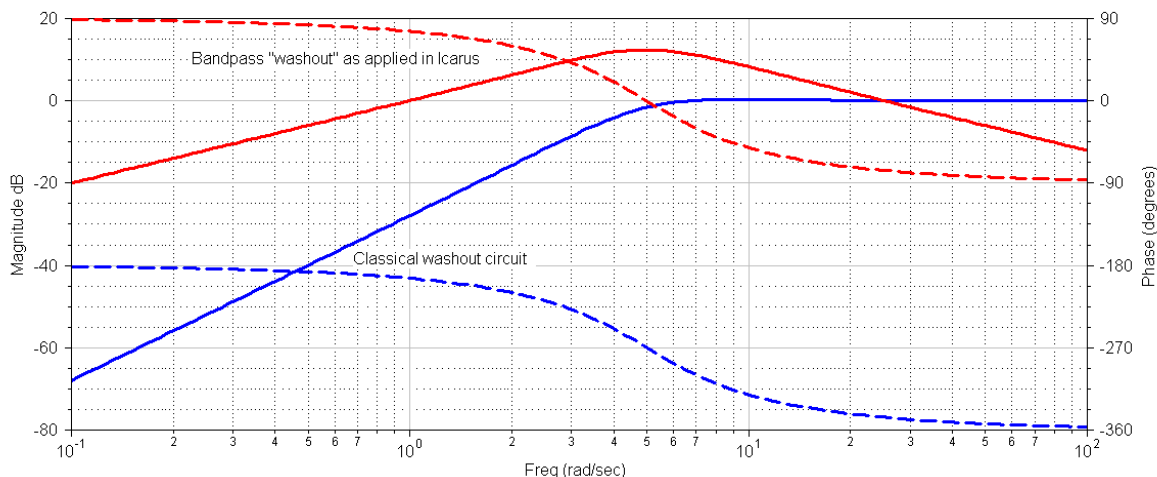
Washout circuits can be of varying order; the higher the order, the more variables available to the designer to modify the basic dynamic response characteristics, but the more variables to track as well. For this project, the format was kept very simple, with a first-order lead and a second-order lag circuit, as follows:

$$G(s) = \frac{\omega_{wo}^2 s}{s^2 + 2\zeta_{wo} \omega_{wo} s + \omega_{wo}^2}$$

This form of filter is different from textbook washout circuits, such as those applied to motion-base algorithms for simulators;^{i,iii} in those cases, the numerator would also be second-order, so that the steady-state response is unity and only the output below the break frequency is attenuated:

$$G(s) = \frac{s^2}{s^2 + 2\zeta_{wo} \omega_{wo} s + \omega_{wo}^2}$$

The use of a first-order zero makes the selected circuit more like a bandpass filter, where maximum throughput is around the break frequency, ω_{wo} , with attenuation both below and above the break frequency. Frequency response comparisons of the two filter forms are shown in the following sketch (using a damping ratio of $\zeta_{wo} = 0.6$ and break frequency of $\omega_{wo} = 5$ rad/s; solid lines are magnitude and dashed lines are phase angle):



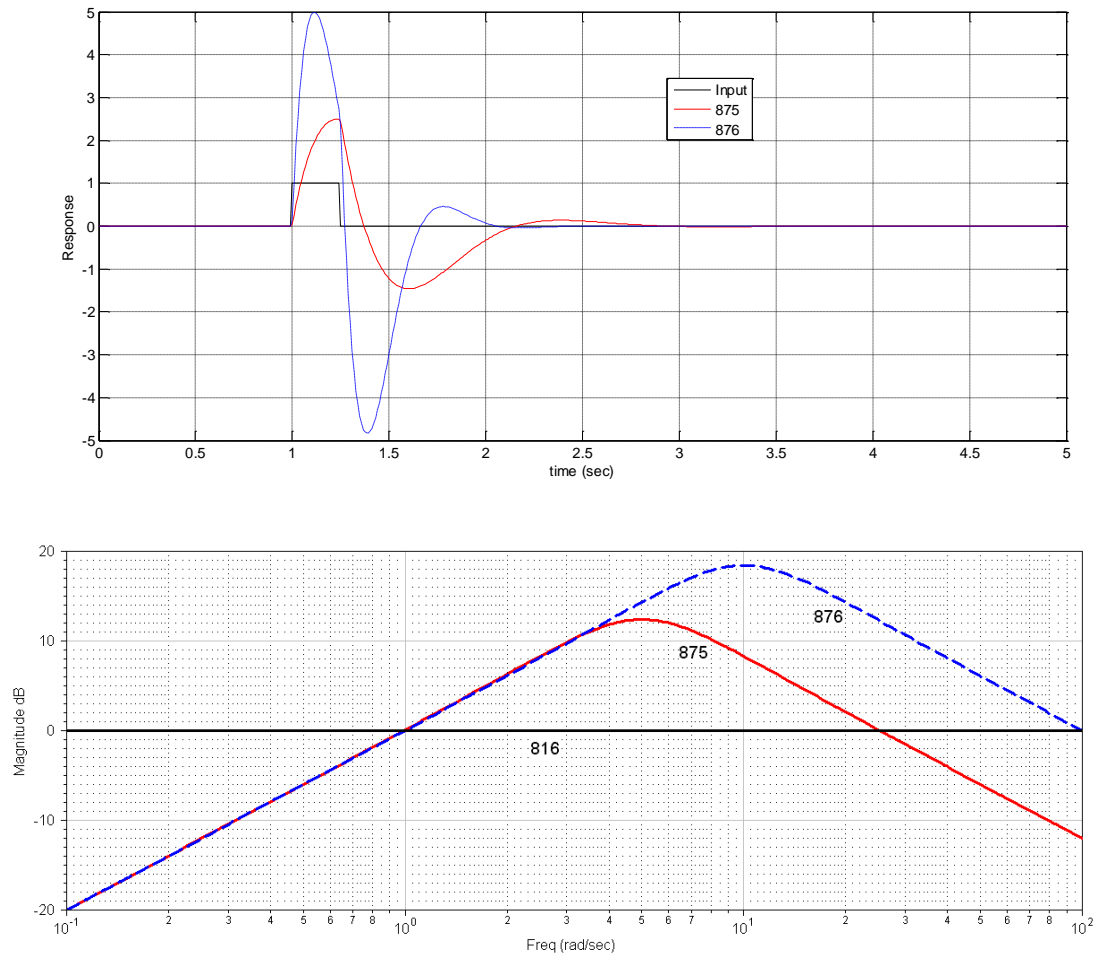
The washout filter (blue lines) has unity throughput gain (0 dB) at high frequencies and attenuates the magnitude at low frequencies. By contrast, the bandpass/washout filter (red lines) attenuates at all frequencies except the break frequency of 5 rad/s; the addition of the square of washout frequency in the numerator of the bandpass filter has the effect of amplifying the response near the break frequency, but this amplification is changed by the stick crossfeed gain used in the Icarus design.

Even with only a second-order filter, there are many possible responses, as damping ratio and undamped natural frequency (break frequency) can be varied over a wide range. To keep things simple, damping ratio was held constant at 0.6 and two frequencies, 5 and 10 rad/s, were used. These numbers were first evaluated in a simulation at NASA Dryden Flight Research Center and were determined to be sufficient to expose effects of high-order coupled dynamics.

The following two sketches show the time response characteristics of the two selected circuits (identified in the experiment matrix as Configurations 875 and 876), where the input is a unit pulse of 0.25 second duration applied at 1 second, and frequency response characteristics of their magnitudes. As the time histories clearly show, the lower-frequency Configuration 875 also has a lower amplitude, but it takes longer for the response to wash out. By contrast, the higher-frequency Configuration 876 has a higher amplitude but it returns to zero more rapidly.

The frequency responses clearly illustrate the reasons these dynamics were so interesting: unlike a straight stick crossfeed – which would be at unity amplitude (0 dB on the sketch) at all frequencies (Configuration 816) – the filters are less responsive at very high and very low frequencies. This frequency response can be interpreted as the ideal interaxis coupling ratio, either p/q or q/p ; the unity stick crossfeed of 816 has 0 dB of coupling, no matter what the measurement frequency, but the measured coupling for the filter cases will depend heavily on the frequency range over which the coupling is measured. For example, suppose the bandwidth and neutral-stability frequencies were 1 and 4 rad/s, respectively;

the measured crosscoupling for the two filters would be almost identical. On the other hand, if the two frequencies were 4 and 8 rad/s, 876 would have much higher measured coupling than 875. And if the frequencies were very low – below 1 rad/s – both would have lower measured coupling than the constant-amplitude 816.



These filters provide the opportunity to exercise the dynamic response characteristics of cross-axis coupling, and to do so with high-order dynamics.

- ⁱ Mitchell, David G., Roger H. Hoh, Adolph Atencio, Jr., and David L. Key, *Ground-Based Simulation Evaluation of the Effects of Time Delays and Motion on Rotorcraft Handling Qualities*, USAAVSCOM TR-91-A-010, Jan. 1992.
- ⁱⁱ Schroeder, Jeffery A., *Helicopter Flight Simulation Motion Platform Requirements*, NASA/TP-1999-208766, July 1999.

(End of reference 7)

Following is an example:

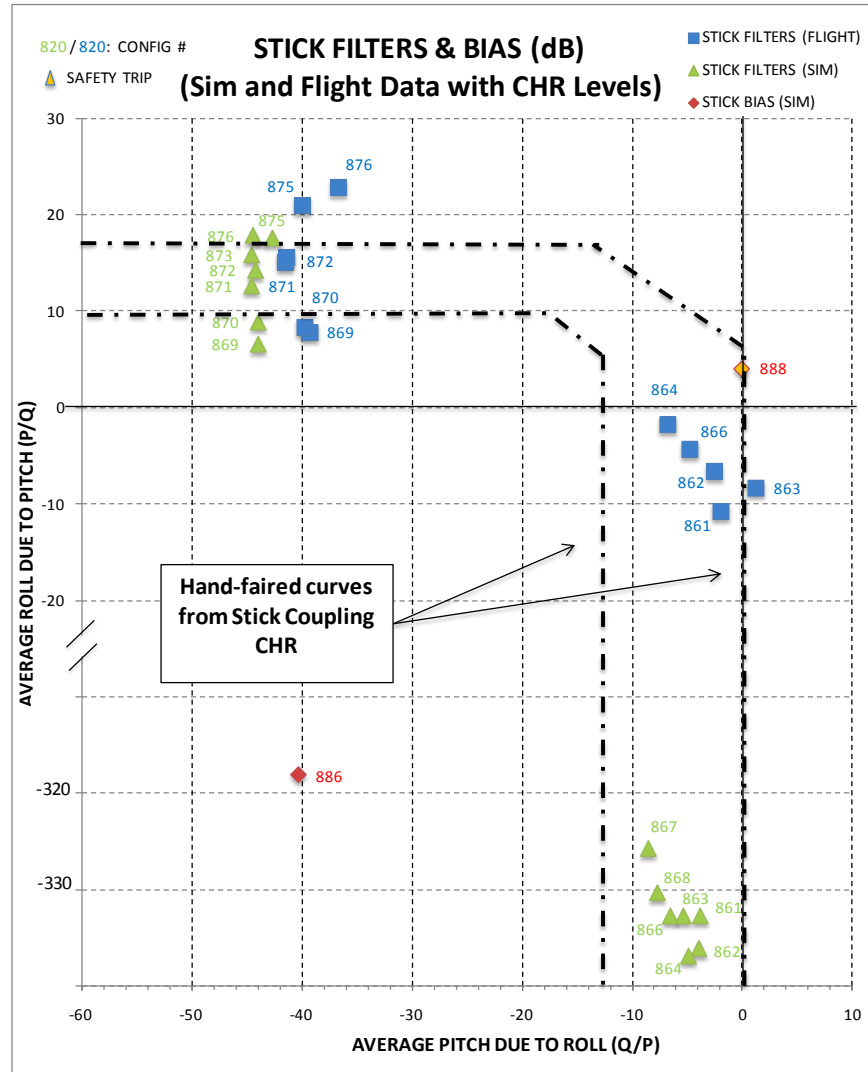


Figure L-1. Stick Filters and Bias (dB) – Sim and Flight Data with CHR Levels

Consider configurations 875 and 876. The first consisted in configuration 816 with the addition of the 5 rad/sec filter, whereas the second one had the 10 rad/sec filter. While configuration 816 gave a consistent CHR of 4, both filters led to ratings of 5 and 6 and up to 9. The above chart shows the CHR levels derived from pure stick and rate coupling; configurations 875 and 876 effectively showed up in a worse region than configuration 816 (see figure L-1), supporting pilot comments. Also configurations 869 and 870, corresponding to 813 (good level I with CHR of 3), showed a greater roll due to pitch coupling (almost level II), which led to ratings of 4 and 5. Overall, it is evident the worsening of the ratings given by the filtered signal. The metric, as it is, was able to catch the „apparent“ increased coupling (due to the filters), but the levels identified were not perfectly comparable to the ones identified with the pure coupling configurations. Further investigation is necessary to adapt the metric for use with dynamics similar to the ones addressed. See lessons learned (appendix P) for further details.

APPENDIX M: DATA ANALYSIS PROCEDURES

Data requirements:

Pilot comments and VISTA-recorded data are required, with the most important being:

1. Stick-coupling:
 - Stick deflections (δ_{es} & δ_{as})
 - Stick cross-coupling signals (roll_per_pitch_rt & pitch_per_roll_rt)
 - Stick total commanded signals (actual deflection plus cross-coupled component)
 - Stick time delay values (pitch & roll)
 - Stick filter values (pitch & roll)
 - Stick bias values (pitch & roll)
2. Rate-coupling:
 - Commanded q_{dot} & p_{dot} (q_{dot_ff} & p_{dot_ff})
 - Cross-coupling signals for q_{dot} & p_{dot} ($de_per_p_rt$ & $da_per_q_rt$)
 - Total commanded q_{dot} & p_{dot} (q_{dot_cmd} & p_{dot_cmd})
 - Rate coupling time delay values (pitch & roll)
 - Rate filter values (pitch & roll)
 - Rate bias values (pitch & roll)
3. Task performance:
 - Primary task (discrete tracking) commanded pitch and roll signals
 - Primary task (discrete tracking) pitch and roll error signals (performances)
 - Secondary task commanded signal
 - Secondary task input signal (by the pilot)
4. Aircraft parameters:
 - Configuration number
 - Pitch attitude (θ)
 - Roll attitude (ϕ)
 - Pitch rate (q)
 - Roll rate (p)
 - Altitude (H)
 - Airspeed (V)
 - Time stamp (τ)
 - Rudder deflections
 - Angle-of-attack (α)
 - Angle of sideslip (β)
 - Load factor (N_z)
 - Mach number (M)
 - Fuel weight (lbs)
 - PTI values (amplitude, period...)
 - Surfaces deflections

Data reduction process:

The data reduction process consists of four distinctive steps. First, a series of pitch and roll sweeps are executed at each test condition in order to collect time histories of stick deflections and aircraft pitch and roll response; with the data collected, the test point can then be located in a chart of q/p against p/q , in ADS-33E-PRF (paragraph 3.4.5.4) format. Second, all data concerning the primary and secondary tasks are recorded in order to quantitatively assess pilot's performance and workload post-flight. Third, pilots comments and ratings are collected during the flight. Fourth, all available data are matched with the specific test points to define possible boundaries between Handling Qualities regions in the aforementioned chart. Following are the details of the first two steps:

1. Locating the test point on the ADS-33E-PRF chart (i.e. Baseline aircraft):
 - a. At each test point two files are generated from a roll and a pitch frequency sweeps (PTI), each containing time-stamped stick roll (pitch) deflection, aircraft roll (pitch) rate and roll (pitch) attitude. Both files are processed in MATLAB
 - b. First, the ratio of **roll-due-to-pitch** is computed (mean p/q):
 - i. Roll frequency sweep is loaded (time histories of ϕ & δ_{as})
 - ii. Fast Fourier Transforms (FFT) and Power Spectral Density (PSD) are used to generate frequency-domain Bode plots of ϕ/δ_{as}
 - iii. Neutral point (phase=-180°), gain margin (6dB) and phase margin (45°) are computed on the above plot and the bandwidth (BW) for the ϕ/δ_{as} transfer function is identified (being the range of frequencies included between the lesser of the two margins and the neutral point, shown in red on the magnitude plot). See figure M-1.

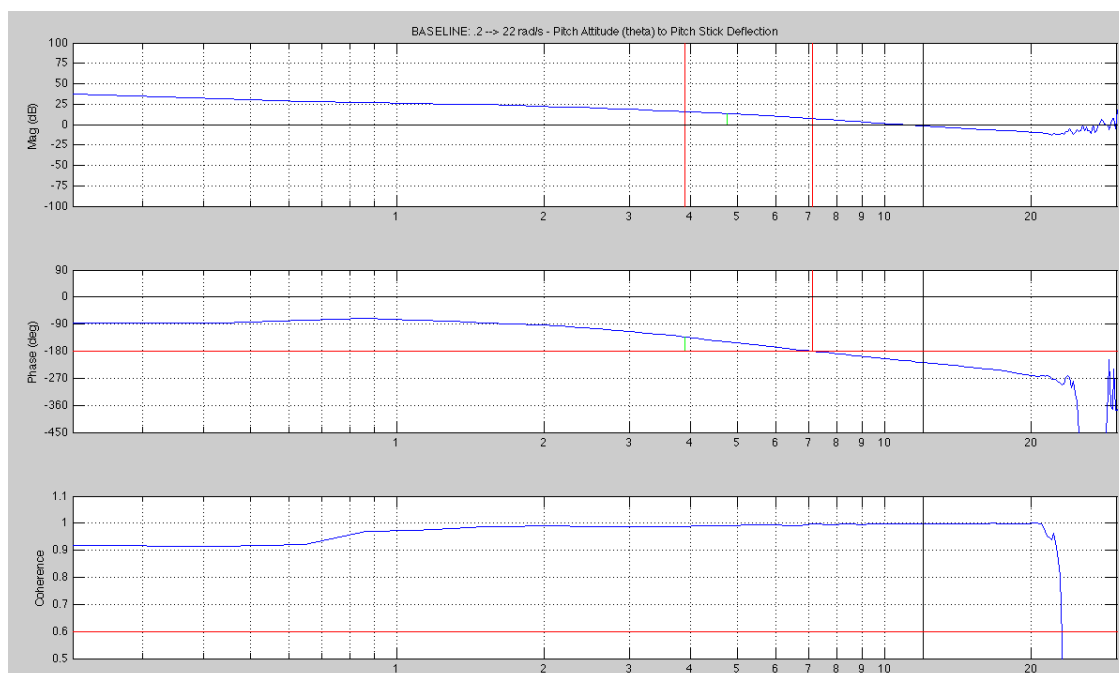


Figure M-1. Baseline Pitch Axis Bode Plot

- iv. Pitch frequency sweep is loaded (time histories of δ_{es} , q and p)
- v. Fast Fourier Transforms (FFT) and Power Spectral Density (PSD) are used to generate frequency-domain Bode plots of $\mathbf{p/q}$
- vi. The Log Magnitude curve from the plot is converted into linear numbers and its average over the bandwidth defined in step b-iii. is computed
- vii. Averaged magnitude of roll response is transformed back into dB (mean p/q), and represents *the response in roll (averaged within the roll stability bandwidth) due to a pitch input*
- c. Next, the ratio of **pitch-due-to-roll** is computed (mean q/p):
 - i. Pitch frequency sweep is loaded (time histories of Φ & δ_{es})
 - ii. Fast Fourier Transforms (FFT) and Power Spectral Density (PSD) are used to generate frequency-domain Bode plots of Φ / δ_{es}
 - iii. Neutral point (phase=-180°), gain margin (6dB) and phase margin (45°) are computed on the above plot and the bandwidth (BW) for the Φ / δ_{es} transfer function is identified (being the range of frequencies included between the lesser of the two margins and the neutral point) See figure M-2.

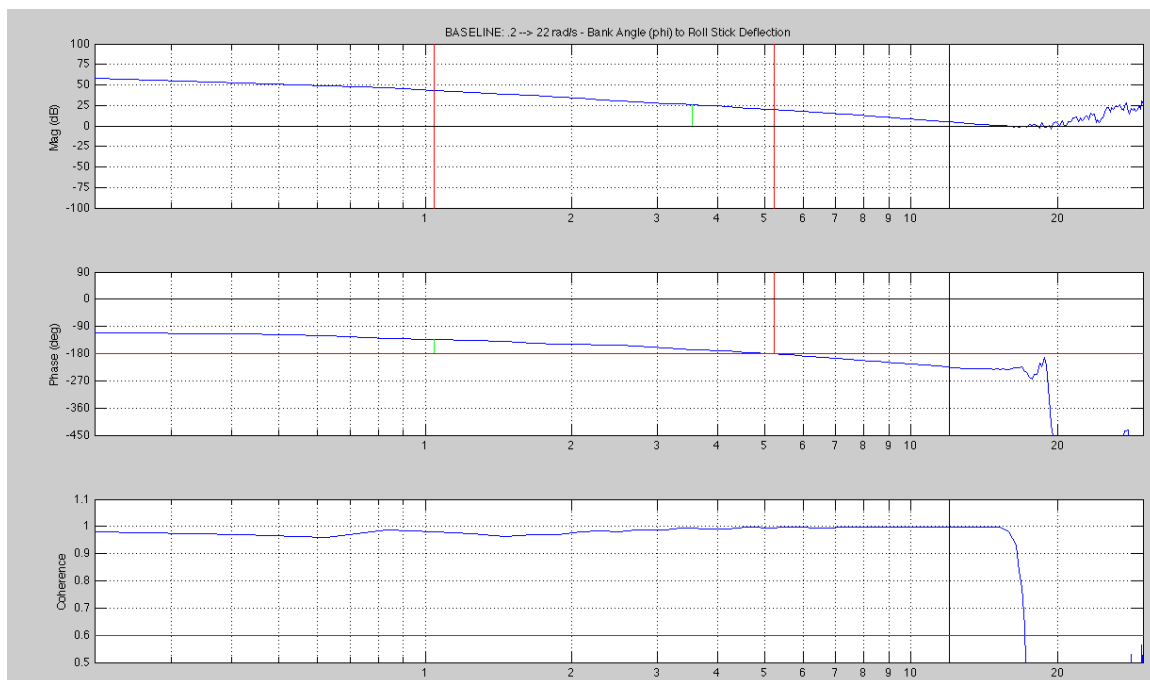


Figure M-2. Baseline Roll Axis Bode Plot

- iv. Roll frequency sweep is loaded (time histories of δ_{as} , p and q)
- v. Fast Fourier Transforms (FFT) and Power Spectral Density (PSD) are used to generate frequency-domain Bode plots of $\mathbf{q/p}$

- vi. The Log Magnitude curve from the plot is converted into linear numbers and its average over the bandwidth defined in step c-iii. is computed
- vii. Averaged magnitude of roll response is transformed back into dB (mean q/p), and represents *the response in pitch (averaged within the pitch stability bandwidth) due to a roll input*
- d. Finally, the test point (identified by the x-value of q/p and the y-value of p/q) is plotted on the ADS-33E-PRF chart (figure M-3)

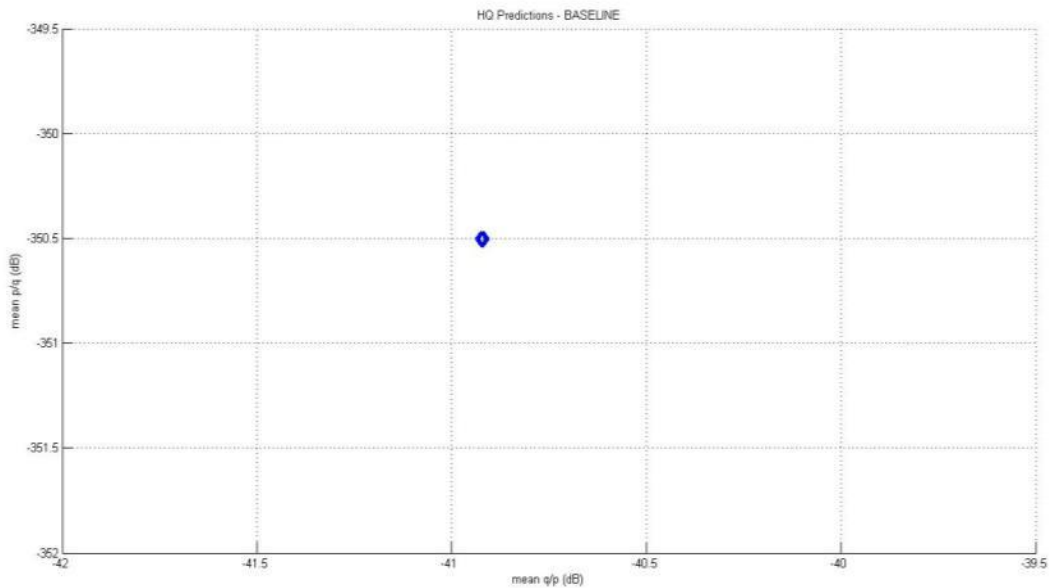


Figure M-3. Baseline Configuration on ADS-33E-PRF

- e. The whole process is repeated for all the test points and is shown here in both logarithmic (figure M-4a) and linear scales (figure M-4b):

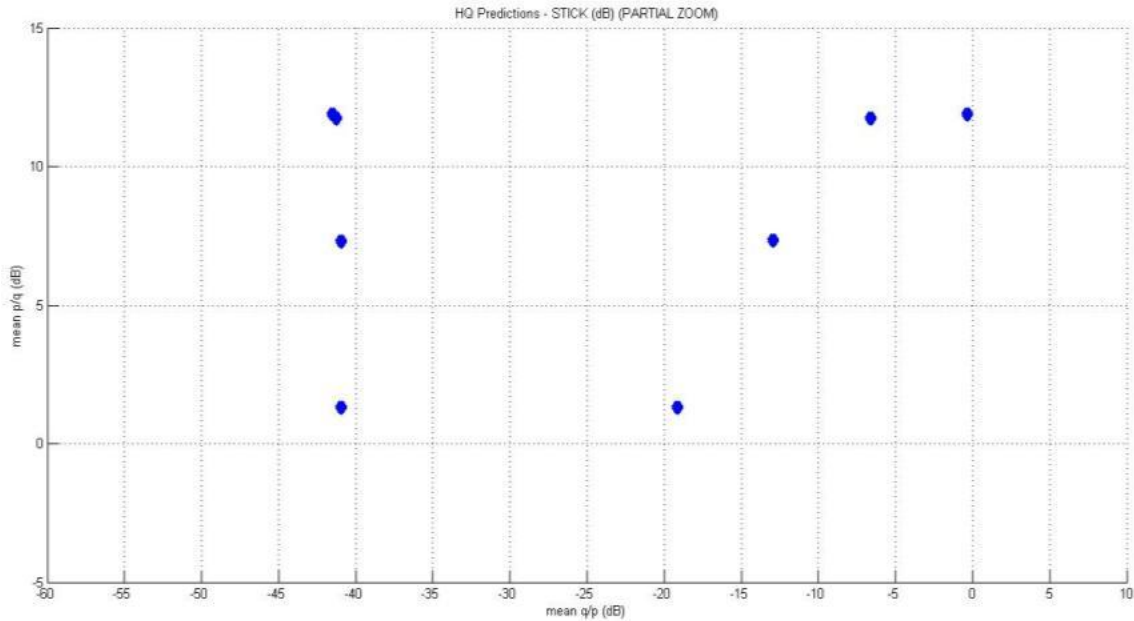


Figure M-4a. Various Configurations on ADS-33E-PRF

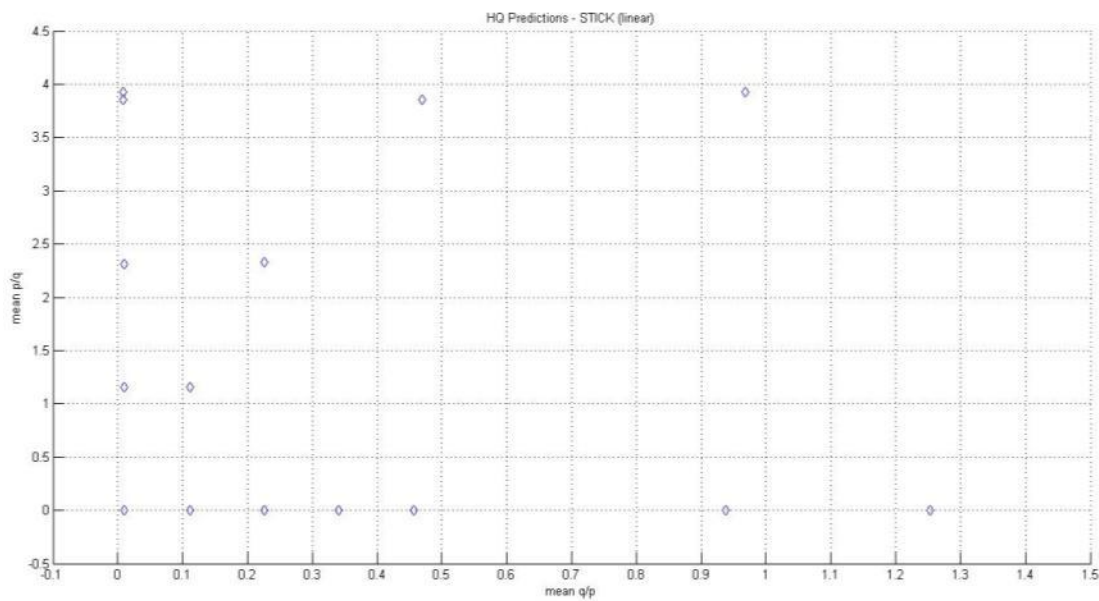
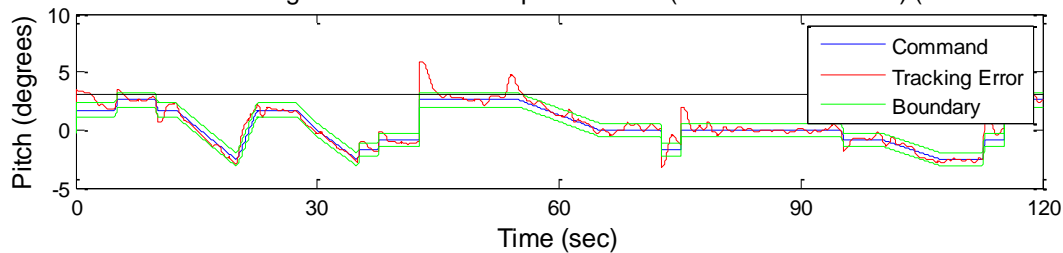


Figure M-4b. Various Configurations on Linear Scale Chart

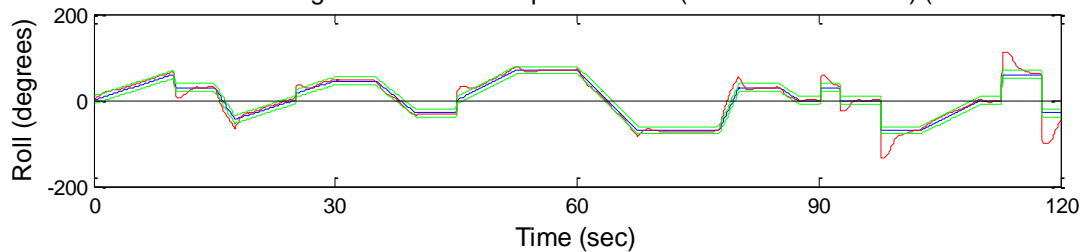
2. Measuring pilot performance (example: figure M-5 thru M-7):
 - a. Four data vectors are recorded in-flight (Pitch and Roll Discrete Tracking)
 - i. Pitch Command Data Vector (sampling rate 50 Hz)
 - ii. Pitch Pilot Input Data Vector (sampling rate 50 Hz)
 - iii. Roll Command Data Vector (sampling rate 50 Hz)
 - iv. Roll Pilot Input Data Vector (sampling rate 50 Hz)

- b. Upper and lower bounds are set as a reference off of the pitch and roll command points to define performance
 - c. Each pilot input data point is compared with its respective pitch or roll boundaries
 - i. If input point falls within the boundaries, a “successful hit” is recorded
 - d. Once all points are processed, total percentages are calculated for pitch and roll tracking performance
3. Measuring pilot workload (example: figure M-5 thru M-7):
 - a. Two data vectors are recorded in-flight (Secondary Workload Task)
 - i. Up/Down/Left/Right Command Data (sampling rate 50 Hz)
 - ii. Pilot Input Data Vector (sampling rate 50 Hz)
 - b. The command data presented to the pilot are updated every 3 seconds
 - c. Each pilot input data point is compared with its respective command data point
 - i. If input point matches with the command data point at any time before the next command data point is updated (3 seconds), a “successful hit” is recorded
 - d. Once all points are processed, total percentage is calculated for secondary workload performance

PRIMARY TASK - Percentage of Correct Pitch Input: 81.34 % (Pitch & Roll: 66.6 %) (Desired Boundary)



PRIMARY TASK - Percentage of Correct Roll Input: 80.68 % (Pitch & Roll: 66.6 %) (Desired Boundary)



SECONDARY TASK - Percentage of Correct Input: 92.5 %

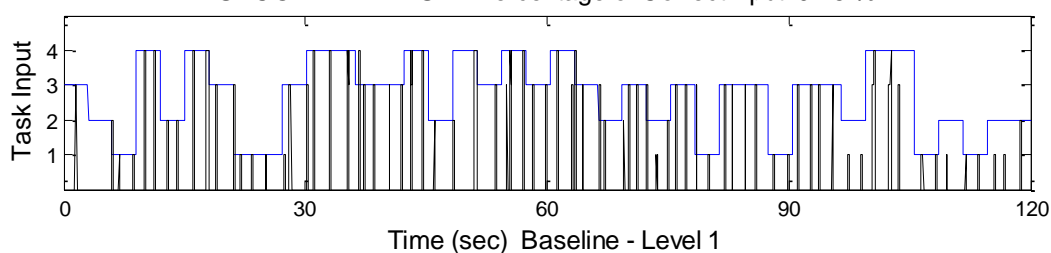
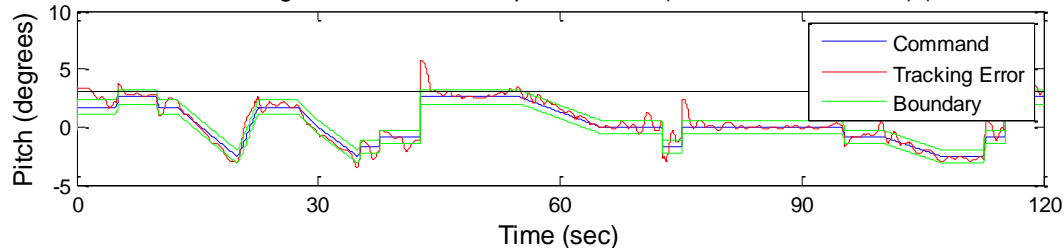
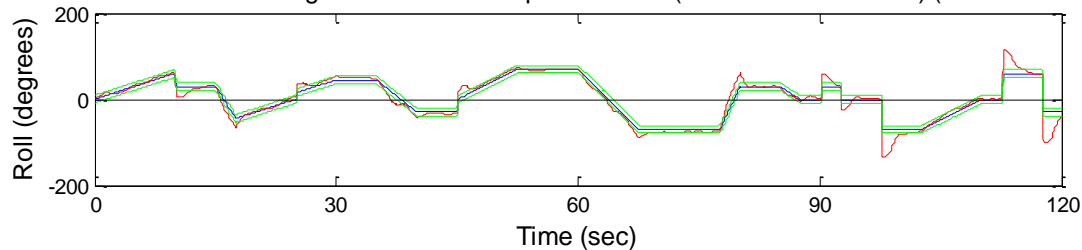


Figure M-5. Example of Level I Primary and Secondary Task Performance

PRIMARY TASK - Percentage of Correct Pitch Input: 77.03 % (Pitch & Roll: 56.65 %) (Desired Boundary)



PRIMARY TASK - Percentage of Correct Roll Input: 74.63 % (Pitch & Roll: 56.65 %) (Desired Boundary)



SECONDARY TASK - Percentage of Correct Input: 97.5 %

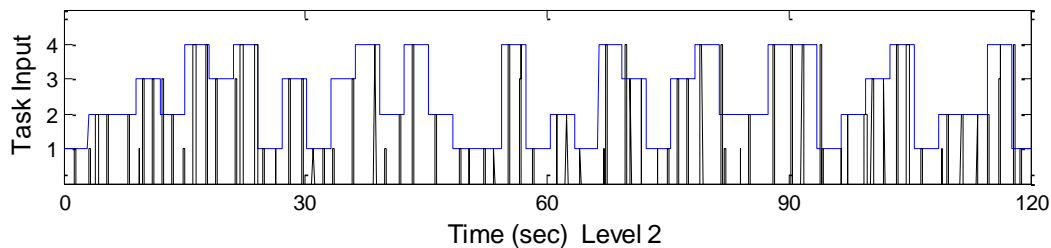
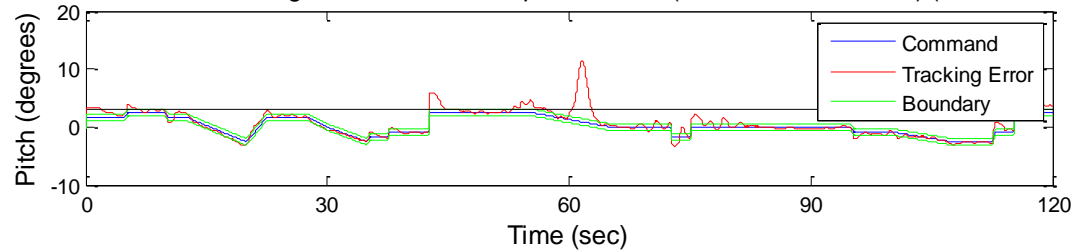
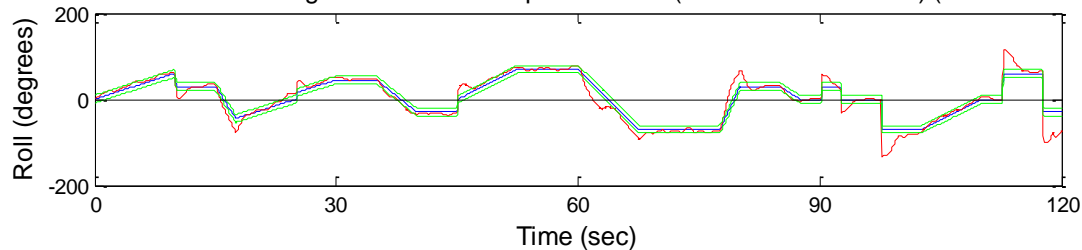


Figure M-6. Example of Level II Primary and Secondary Task Performance

PRIMARY TASK - Percentage of Correct Pitch Input: 68.21 % (Pitch & Roll: 44.86 %) (Desired Boundary)



PRIMARY TASK - Percentage of Correct Roll Input: 68.91 % (Pitch & Roll: 44.86 %) (Desired Boundary)



SECONDARY TASK - Percentage of Correct Input: 92.5 %

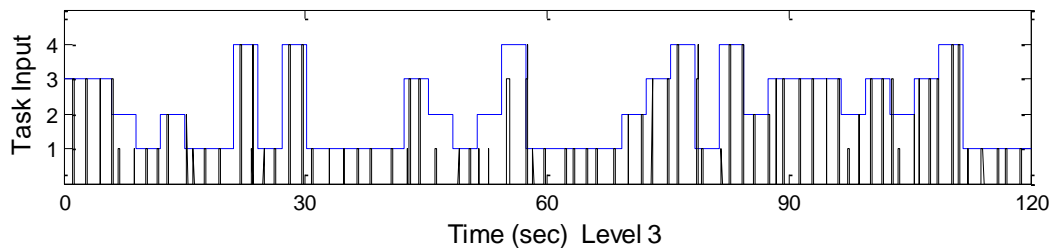


Figure M-7. Example of Level III Primary and Secondary Task Performance

APPENDIX N: GROUND SIMULATION

Procedure

The Icarus software model was loaded on the TPS handling qualities simulator and its implementation of cross-coupling was verified to be as described in the Research Software section above. The model was fine-tuned during this phase of the test. For example, it was during the ground simulations that the need to “down-gain” the rate coupling via *de_per_p_nom_rt* and *da_per_q_nom_rt* was discovered.

The ground simulation events were used primarily to develop the test matrix. This was accomplished by the engineers selecting numerous cross-coupling gain values for the pilots to fly in the simulator. The gains were varied to determine at what values the pilots encountered level I, II, and III handling qualities for each type of coupling implementation (stick, rate, filters, and bias). For each coupled scenario, the pilots assigned a CHR and PIOR and provided comments related to the handling qualities.

More than 230 scenarios were flown during ground simulation using the procedure described above. The CHRs associated with these scenarios were compared to determine approximate level I, II, and III regions as shown on figures N-1 and N-2. The test matrix configurations were then created to achieve a relatively even dispersion of gain values across the regions for stick and rate coupling. The configurations were numbered from 801 to 892. These configurations and all associated gain values are listed in appendix A. Configuration 801 was established as the baseline (no induced coupling) configuration. For this configuration, all coupling gain values were equal to zero, with a few exceptions. The non-zero gains in this configuration were those required to make the filters equal 1 plus the nominal scaling gains in the rate coupling remained unchanged.

Twenty primary stick coupling configurations, plus nine backup stick coupling configurations were created. The primary configurations were those intended to be evaluated during the flight tests. The backup configurations were created to allow flexibility to either fly additional configurations if able or shift the primary point’s gain value based on flight results without requiring reprogramming of the configuration. Configurations 802 to 812 induced pitch due to roll stick coupling. Configurations 813 to 822 were roll due to pitch stick coupling. Configurations 823 to 830 had both pitch due to roll and roll due to pitch stick coupling (two-axis coupling).

Nine primary rate coupling configurations plus 21 back up rate coupling configurations were created. Configurations 831 to 860 were the rate coupling configurations, with 831 to 842 being pitch due to roll, 843 to 853 being roll due to pitch, and 854 to 860 being dual-axis.

The filter configurations were selected by choosing predicted level II stick and rate coupling points as the basis. Four primary and four backup stick filter configurations were created, each being evaluated for two filter types (16 total points). Two primary and two backup rate filter configurations were created, each being evaluated for two filter types (eight total points). Configurations 861 to 876 were the stick coupled configurations with added filtering.

Configurations 877 to 884 were the rate coupled configurations with the addition of the same filters mentioned above.

The bias configurations were selected to give an approximate 25 percent and 50 percent addition to stick and rate coupling, based on 100 percent representing the maximum available stick input or rate input as appropriate to the model and axis affected. Two primary and two backup bias configurations for each of stick and rate coupling were created (eight total points). Configurations 885 to 888 added bias in the stick coupling block, whereas configurations 889 to 892 added bias in the rate coupling block.

Only the predicted Cooper-Harper level region was considered during selection of the configurations, not where these configurations would fall on the ADS-33E-PRF (paragraph 3.4.5.4) format chart.

Pitch and roll frequency sweeps were performed on each of the configurations via PTIs to characterize the open-loop dynamics of the coupled configurations. The frequency range of the sweeps was from 0.2 rad/sec to 12 rad/sec for configurations 802 to 892 and 0.2 to 22 rad/sec for configuration 801. With the available data a script was built to plot the above scenarios on an ADS-33E-PRF-like chart (cross-coupling plot). A single point on the chart represented a specific configuration whose attributes were: magnitude of pitch rate due to roll rate (x-axis, or q/p), and magnitude of roll rate due to pitch rate (y-axis, or p/q). Also, the same data produced four Bode plots per test configuration: q/p , p/q , $\dot{\phi}/\delta_e$, $\dot{\phi}/\delta_a$.

Results and Analysis

The SIMULINK[®] implementation of the stick coupling produced the expected results: a pure pitch input caused a corresponding rolling motion and vice-versa. Pilots were able to fly the tracking tasks and give Cooper-Harper and PIO ratings. Pilot performance was measured by the software, but only the pitch axis tracking error percentages were shown on the HUD after completing the task. The roll axis scores were not implemented on the HUD. These data could only be recovered post-flight. For this reason, pilots qualitatively assessed their performance to assign the CHR.

The rate coupling implementation was more problematic. Due to a difference in VISTA between the rates in the forward loops (\dot{p} & \dot{q} , i.e. commanded rate accelerations) and the sensed rates in the feedback loops (p & q , i.e. plain rates), there was a need to use the gains *de_per_p_nom_rt* and *da_per_q_nom_rt* to appropriately proportion the signals. Doing so, the feedback signals causing the cross-coupling were comparable in magnitude to the signal in the forward loop on which they were being summed. Even then, the scenarios with high dual-axis coupling gains were inherently unstable (the pitch and roll rates feeding back into each other substantially resembled a positive feedback system). These scenarios were rated as level III by the pilots, and were therefore only tested in a limited amount in-flight.

The washout filters generally caused worse performance by the pilots: the filter prevented the pilot from compensating for a constant amount of coupling throughout. As a result, the pilot initially fought the coupling but then ended up fighting the correction caused by the filter, with a

definite reduction in predictability. The response to inputs was described as a jerkiness in the aircraft motions.

Simulator tests showed that the bias points looked similar to an untrimmed condition. Pilots were able to identify the failure and compensate for it, hence the Test Team elected to fly only a selected amount of these configurations.

The Cooper-Harper level regions shown in figures 3 and 4 below were based on compiled results from all project pilots' simulator flights. The CHRs and PIORs followed an increasing trend with increased amounts of coupling. This trend was in-line with the trend of the ADS-33E-PRF specification (paragraph 3.4.5.4), though the p/q and q/p values at which the region divisions occurred were only estimated at the time of test matrix development. To guarantee data validity and sustainable results, the points were selected according to pilots comments and ratings, hence the actual gain values rather than the resultant p/q and q/p, which were very dependent on the frequency characterization of the response, were used to develop the test matrix. The cross-coupled configurations (801 to 892) were built to fit within these estimated Cooper-Harper level I, II, and III regions. The configurations are shown on figures N-1 and N-2 below.

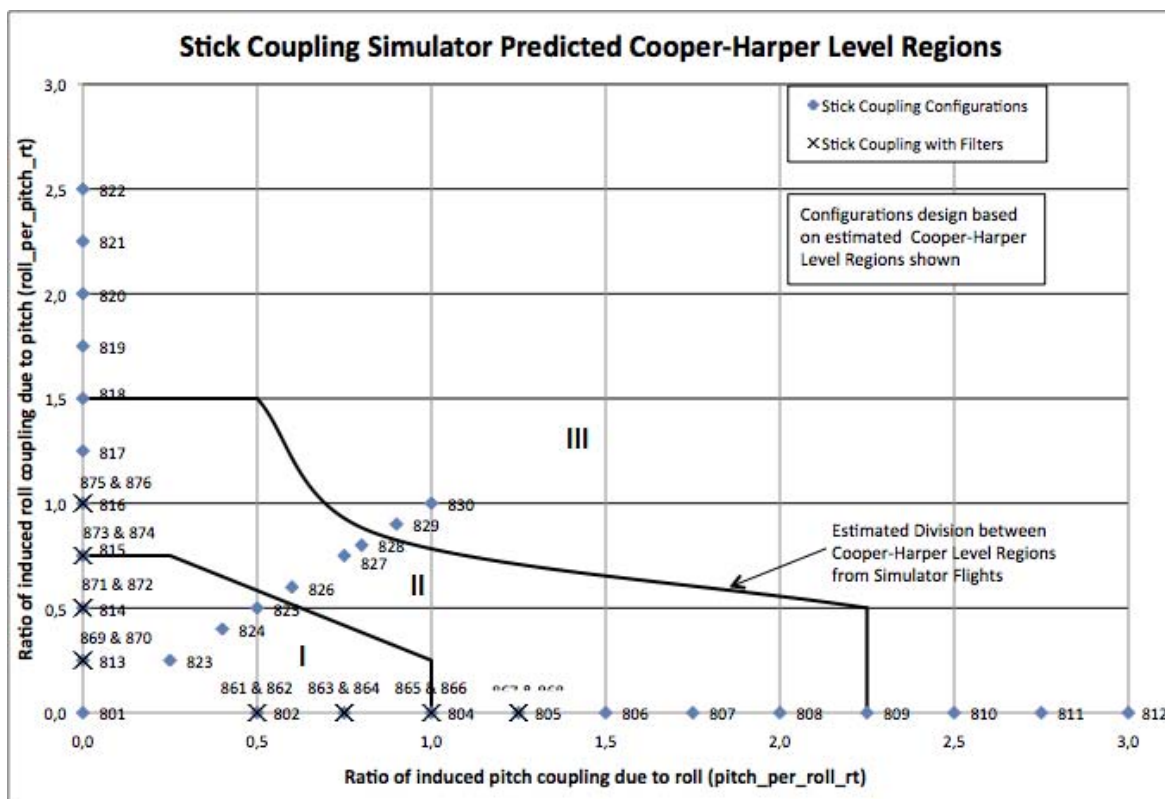


Figure N-1. Predicted Regions of Cooper-Harper Levels (Stick)

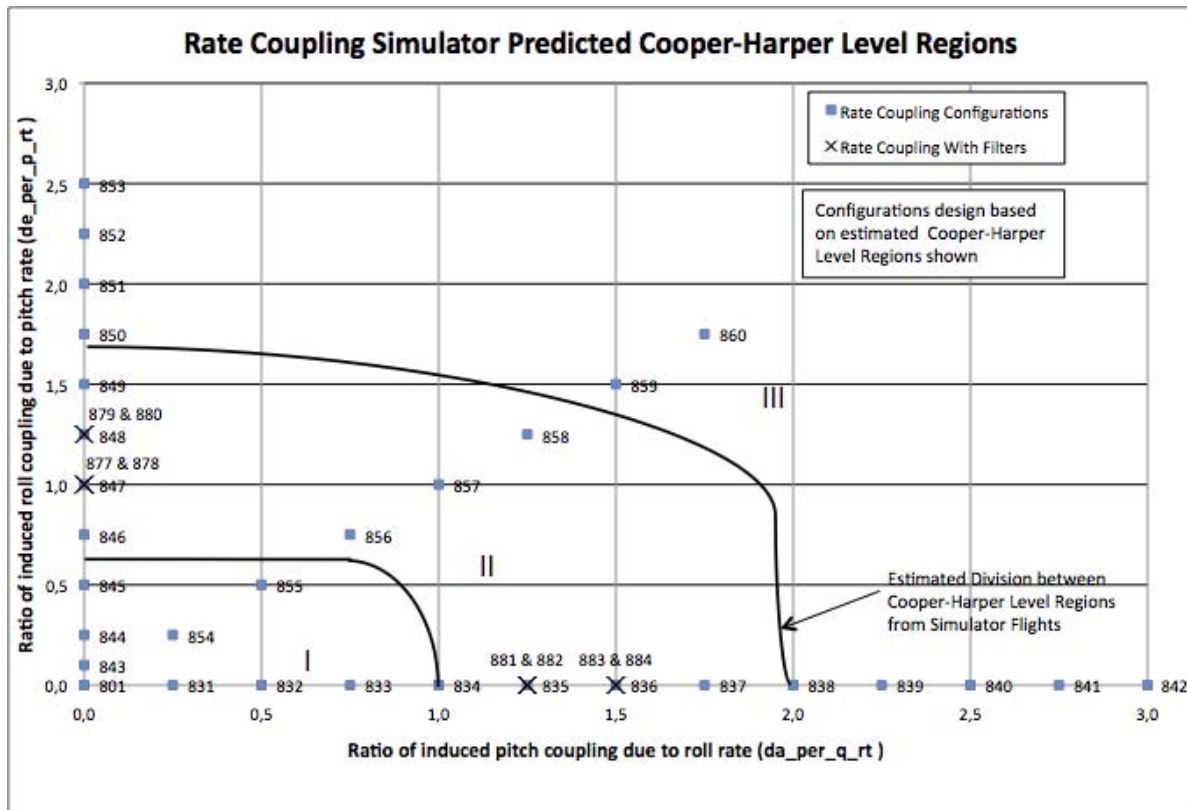


Figure N-2. Predicted Regions of Cooper-Harper Levels (Rate)

Once the test matrix configurations were determined as described in the procedures above, the points were plotted on the ADS-33E-PRF (paragraph 3.4.5.4) format charts (appendix F) described in the flying qualities section below using the simulation model to perform the frequency sweeps in SIMULINK®, and using the data reduction process on the resultant data as described in appendix K. One difficulty encountered during these sweeps was for the filter coupling configurations; the frequency sweeps were encountering surface movement rate limits after approximately 1.5 seconds into the sweep. In order to complete the sweep to fully characterize the coupled conditions and plot the points on the ADS-33E-PRF (paragraph 3.4.5.4) charts, the rate limiters were disabled in the SIMULINK® software model.

APPENDIX O: PITCH AND ROLL DISCRETE TRACKING TASK

The following Pitch and Roll Discrete Tracking Task Description is from *Handling Quality Demonstration Maneuvers for Fixed Wing Aircraft*, WL-TR-97-3100 (reference 1).

35. PITCH AND ROLL DISCRETE TRACKING

Tracking a computer-generated command signal produces a highly repeatable, precise task. Two of the most common types of tracking commands are the Calspan Corporation step-and-ramp (discrete tracking) and a sum of sinewaves. The discrete task was found in two USAF TPS projects (Refs. 35.1 and 35.2) to be better at producing repeatable, consistent pilot ratings. The sum-of-sines (SOS) task is considered a more robust form of command for extracting pilot/vehicle information. The latter is presented in a separate demonstration maneuver (MTE 36).

The discrete tracking task has been developed and refined by Calspan Corporation over the years, from the "Neal-Smith" task (Ref. 35.3) in pitch, to "LATHOS" (Ref. 35.4) in roll, and a pitch-and-roll combination (Ref. 35.5). The two-axis version presented here is the most recent, flown in both Refs. 35.1 and 35.2. Many of the subtleties of the task, apparently never published in any Calspan Corporation report, were provided by Calspan Corporation to the authors of Ref. 35.2 and are repeated here.

Ideally, the display for this maneuver will be a head-up display (HUD) with an appropriate command bar and fixed pipers for desired and adequate performance. Realistically, however, such a display may be restricted only to experimental and research aircraft, at least for the near future, so the maneuver should not be limited only to HUDs. The display device may be the command bars on a flight director, the glideslope and localizer bars on a horizontal situation indicator, etc. If a HUD is not used, the definitions of command scaling (units of actual error per displayed error) and performance limits become critical. In addition, for any display, the dynamics of the display drivers become important. Total throughput delay should at least be known, even if nothing can be done about it.

Table 35.1 lists the breakpoints for the pitch and roll command signals as a function of time. Plots of the command signals are shown in Figure 35.1. These signals may be scaled as needed to suit the load factor and roll rate ranges under study. In the flight research of Ref. 35.2 (and, apparently, in all studies performed by Calspan Corporation with these command signals), scale factors were applied in both pitch and roll, as described below. For Ref. 35.2, the pitch command resulted in load factors between about 0.3g and 2g. Higher load factors are possible but will begin to require extremely large pilot inputs; lower load factors may not reveal much about the handling qualities of the airplane.

The signal displayed to the pilot is tracking error, not the command. When used by Calspan Corporation, there is a scale factor on the signal before it is displayed as well. In addition, Euler pitch attitude is adjusted for bank angle. In pitch, $\theta_{\text{display}} = K_{e\theta}(\theta_c - \theta' + \theta_{\text{bias}})$, where $K_{e\theta} = 0.86$, θ_c is the command (from the table), θ_{bias} is airplane attitude at the start of the task, and $\theta' = \theta/\cos(\phi)$. In roll, $\phi_{\text{display}} = K_{e\phi}(\phi_c - \phi + \phi_{\text{bias}})$, where $K_{e\phi} = 0.88$, ϕ_c is the command (from the table), ϕ is bank angle, and ϕ_{bias} is airplane bank angle at the start of the task. The display of error, rather than pure command, makes the task compensatory in nature: the pilot compensates for displayed changes in attitude rather than pursuing an attitude command.

Desired and adequate performance limits are written in terms of mils of tracking error and are clearly geared toward a HUD. The format of these requirements is taken from Ref. 35.5, but the numbers are twice those used in Ref. 35.5. It was found in initial shakedown for the tests of Ref. 35.2 that the original limits were too small for the pilots to observe much less attempt to meet.

Single-axis tracking may be performed by zeroing the command signal in one axis. Calspan Corporation recommends, however, that two-axis tracking always be performed to assure good pilot-in-the-loop operations.

TABLE 35.1. BREAKPOINTS FOR DISCRETE TRACKING COMMAND SIGNALS

Time (sec)	Pitch Command (deg)	Roll Command (deg)	Time (sec)	Pitch Command (deg)	Roll Command (deg)	Time (sec)	Pitch Command (deg)	Roll Command (deg)
0	0	0	45	3	-30	92.6	0	0
0.1	2	0.6	45.1	3	0	95	0	0
5	2	30	52.5	3	70	95.1	-1	0
5.5	3	30.6	55	3	70	97.5	-1	0
10	3	60	60	1.5	70	97.6	-1	-70
10.1	2	30	65	0	-23.3	100	-1	-70
12.5	2	30	67.5	0	-70	102.5	-1.67	-70
15	0.33	30	70	0	-70	107.5	-3	-23.3
17.5	-1.33	-45	70.1	0	-70	110	-3	0
20	-3	-30	72.5	0	-70	112.5	-3	0
22.5	2	-15	72.6	-2	-70	112.6	-1	60
25	2	0	75	-2	-70	115	-1	60
25.1	2	15	75.1	0	-70	115.1	3	60
27.5	2	30	77.5	0	-70	117.5	3	60
30	0	45	80	0	30	117.6	3	-30
35	-3	45	80.1	0	30	120	3	-30
35.1	-2	43.5	82.5	0	30	120.1	2	-30
37.5	-2	7.5	85	0	30	122.5	2	-30
37.6	-1	6	87.5	0	0	126.6	1	-15
40	-1	-30	90	0	0	127.5	1	-15
42.5	-1	-30	90.1	0	30	127.6	0	0
42.6	3	-30	92.5	0	30	150	0	0

References:

- 35.1. Randall, Paul A., LT, USN, *et al.*, *A Limited Inflight Investigation of the Neal-Smith Criteria*, AFFTC-TLR-94-27.
- 35.2. Kish, B. A., *et al.*, *A Limited Flight Test Investigation of Pilot-Induced Oscillation due to Elevator Rate Limiting*, AFFTC-TR-97-12, June 1997.
- 35.3. Neal, T. Peter, and Rogers E. Smith, *An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes*, AFFDL-TR-70-74, Volume I, Dec. 1970.
- 35.4. Monagan, Stephen J., Rogers E. Smith, and Randall E. Bailey, *Lateral Flying Qualities of Highly Augmented Fighter Aircraft*, AFWAL-TR-81-3171, June 1982.
- 35.5. Bailey, R. E., and L. H. Knotts, *Interaction of Feel System and Flight Control System Dynamics on Lateral Flying Qualities*, NASA CR-179445, Dec. 1990.

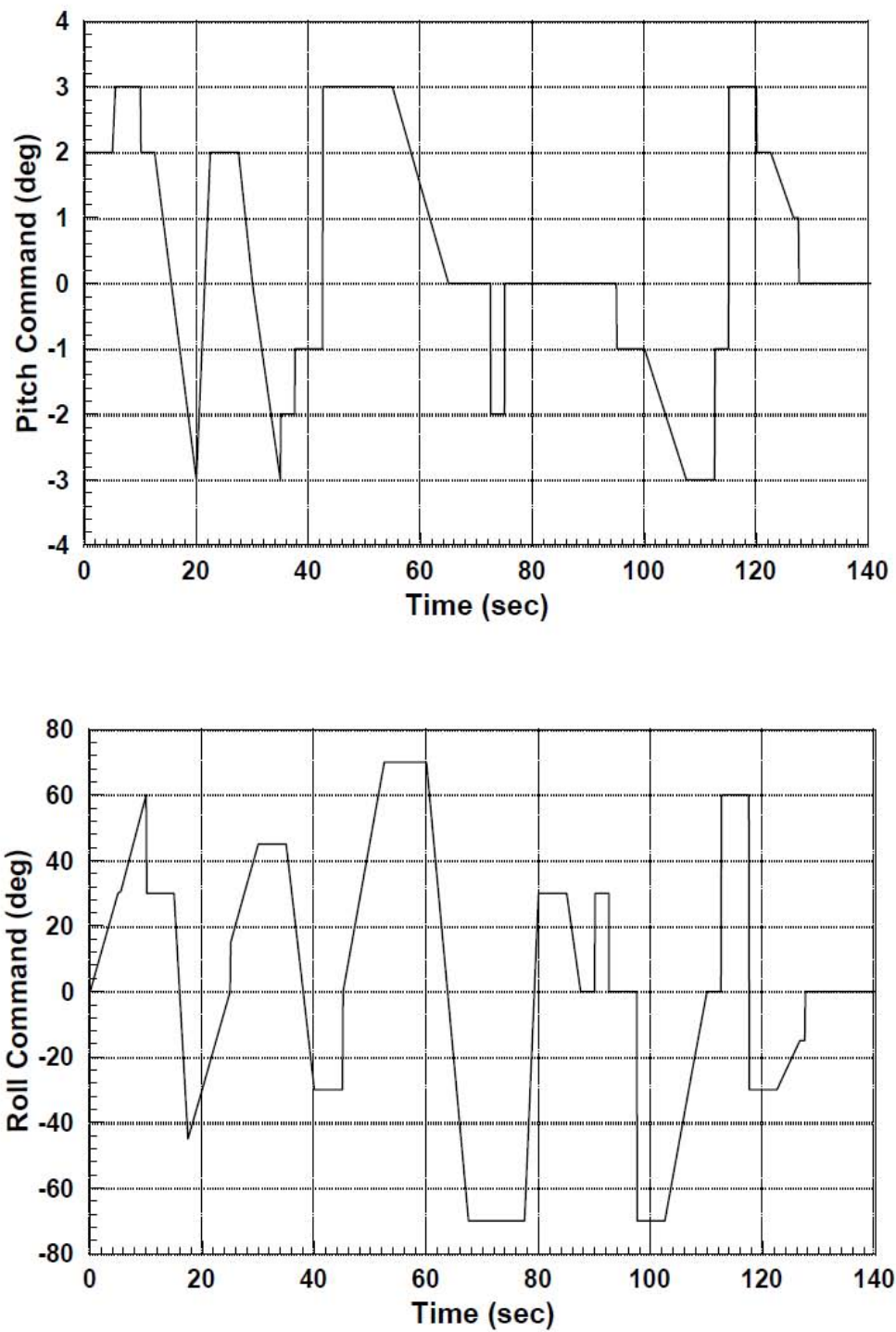


Figure 35.1. Pitch and Roll Axes Discrete Command Signals

35. Pitch and Roll Discrete Tracking

a. Objectives

- Evaluate handling qualities in a tight, closed-loop tracking task.
- Evaluate feel system and control sensitivity characteristics.
- Identify bobble or PIO tendencies.

b. Description

Aggressively track the displayed signal and attempt to keep errors within the specified tolerances.

c. Desired Performance

- ± 10 mils in pitch 50% of the time.
- ± 10 mils in roll (measured at the end of the command bar) 50% of the time.

d. Adequate Performance

- ± 20 mils in pitch 50% of the time.
- ± 20 mils in roll (measured at the end of the command bar) 50% of the time.

e. Variations

Variations of the command signal and performance limits can be applied for other axes, e.g., airspeed, load factor, flightpath, etc. Extension to these axes will require development of new commands and performance requirements.

APPENDIX P: LESSONS LEARNED

Following is a series of lessons learned and related recommendations identified by the Project Icarus team, given in a logical pattern from the simulation phase to the flight phase. They are not to be considered exhaustive nor complete, since they have been collected on a day-by-day basis and some technicalities might have been omitted. For a comprehensive explanation of the above, refer directly to the team members, or to the staff and Calspan representatives at Test Pilot School.

Research Software

Due to the difference in magnitudes of roll and pitch rates attainable with the VISTA, the rate coupling paths were “gained down” to induce a coupling suitable to the off-axis signal magnitude. For example, a one-inch pitch deflection would command a 12 degree change in longitudinal command, corresponding to 22 degrees per second final pitch rate change, whereas the same lateral stick deflection would command only 8 degrees change in lateral command, but up to 120 degrees per second final roll rate change. The roll acceleration command path was therefore gained down by a gain ($de_per_p_rt$) equal to 0.1 ($120^\circ \cdot 0.1 = 12^\circ$) and the pitch acceleration command path was gained down by a gain ($da_per_q_rt$) equal to 0.36 ($22^\circ \cdot 0.36 \approx 8^\circ$). The following table summarizes the procedure used to determine the two gains:

	Stick deflection	δ -command	Generated rate	Gain
Pitch axis	1"	12°	22°/s	0.36
Roll axis	1"	8°	120°/s	0.1

Not doing so, the rate coupling configurations were inherently unstable which would have caused an immediate departure from controlled flight (prevented by the safety trips).

Ground Checkout

The ground checkout was planned to last 8 hours, but required 40 hours to complete. Initial planning anticipated that entering each configuration and verifying values in the VSS computers would be the most time consuming part of the checkout. However, the execution of the frequency sweep PTIs produced unexpected safety trips; an effort to avoid the safety trips by limiting the frequency spectrum and/or identifying a suitable aircraft attitude to begin with was required prior to flight. *Recommend future tests with the VISTA make extensive use of the ground simulation mode, if able, to take advantage of the higher level of fidelity of the VSS computers.*

The PTIs executed in the ground simulation mode of the VSS revealed unforeseen issues with the safety trips built into the VISTA. During the first checkout, the same PTIs used in the simulator to gather open-loop data caused the VSS computer to trip. Most of the time, the safety trips were caused by the stabilators reaching a commanded limit (70 deg/sec for 115 msec of horizontal tail command, and maximum allowed pitch and roll commands), safety trips that were not implemented in the simulator model. The unexpected trips required re-planning of the sweeps: the highest frequency that the VSS was able to produce in the coupled configurations

was 12 rad/sec, hence the sweeps were shaped from 0.2 rad/sec to 12 rad/sec, with a power of one to gather enough data at each intermediate frequency. The sweeps had to be executed from the lowest to the highest frequency to diminish actuator stress. As a result, the dwell time at the low frequency outputs (each PTI had a magnitude of 0.5 inches of stick deflection) created a final aircraft attitude that had to be compensated for with an initial pitch and roll attitude in the opposite direction (generally 10 degrees of pitch up and up to 60 degrees of left roll were required, refer to the test cards in data package for details about each configuration). The purpose was to execute the big part of the sweep close to wings level and on the horizon (i.e. on conditions for the test point). After the ground checkout phase, all the safety trips present in the VSS system were implemented in the simulator model. *Recommend future VISTA test teams verify that all applicable safety trips for the VSS are incorporated in the TPS handling qualities simulator. Suggest investigating the use of manual frequency sweeps to maintain near wings level, as long as the magnitude of coupling is not too strong to deny the pilot the ability to perform the maneuver.*

Also, with the aforementioned PTIs the project team was able to identify the bandwidth frequency for the VISTA in both the pitch and roll axes. On top of this, a limited power spectral density (PSD) analysis was conducted on pilot stick deflections during the primary task. Both of these results, if combined, suggested that the minimum frequency of interest for this type of testing was close to 0.5 rad/sec, which could be used instead of 0.2 rad/sec, hence increasing the dwell time at the low frequencies. *Recommend further investigation of the bandwidth frequency to verify the possibility of using a smaller frequency band for the sweeps, improving data reliability at the very low frequencies.*

It was noted that the handling qualities simulator produced higher stick force per g and larger stick deflection per g than the VISTA in VSS ground mode. The variance in stick deflection and feedback to the pilot affected the workload and performance during primary task execution (less workload in-flight than in the simulator). Test team confidence in simulator CHRs and PIORs was negatively affected. Although some adjustments were made to the stick force gradients following this test, *recommend taking this difference of feel system between the simulator and the aircraft into account for future handling qualities testing.*

Configuration PTIs, primary task, and secondary task data were recorded by the VISTA mission computers and transferred to external drive for analysis. The data reduction process revealed a need to modify the data reduction scripts which had been used for analysis of TPS handling qualities simulator data. The roll axis model had a different implementation than the simulator: in the aircraft a right aileron input (positive) produced an obvious right (positive) roll rate, while the simulator results showed a right aileron input (negative) giving the same right (positive) roll rate. The end result was a 180 degree shift in the phase section of the Bode plots. The problem was fixed by building a set of scripts specifically for the simulator, where a -180 degree shift was injected after the Fast Fourier Transform analysis (see scripts in data package). *Recommend adjusting the simulator model to exactly reflect the signal paths present in VISTA.*

Additionally, the secondary task operation produced an analog signal in the VSS versus a digital signal in the TPS handling qualities simulator (due to a different switch implementation). In order to interpret and record the Target Designator Control (TDC, or cursor slew) position, a new

script utilizing deflection direction and magnitude was created during the checkout. *Recommend future VISTA TMPs utilize scripts created by Project Icarus for data reduction.*

Evaluation of the Use of ADS-33E-PRF Specification (paragraph 3.4.5.4) as a Potential Metric for Fixed-Wing Aircraft

Although the CHR regions were determined to be different, the method of defining them on a chart in the same format and using the same data reduction procedure as the ADS-33E-PRF specification (paragraph 3.4.5.4) was found to be promising. As documented in the Test and Evaluation section, the metric captured most of the stick and rate pure coupling (i.e. no filters or bias) dynamics. An increase in cross-coupling gains always produced degraded handling qualities and subsequently higher CHRs. As a result, the team had good confidence in drawing Cooper-Harper level boundaries based on the results obtained. Obviously, due to the different dynamics of fighter aircraft, and specifically the VISTA, the boundaries were different than the ones identified by the ADS-33E-PRF specification (paragraph 3.4.5.4). This result was somewhat expected and the team was able to quantify the difference for the conditions used in the test.

Some areas of further investigation were identified:

- First, the data reduction procedure was very sensitive to small changes throughout the frequency analysis. The band in which the average coupling was measured depended upon the crossover frequency (phase equal to -180 degrees) and either the gain or phase margin (the one at the lowest frequency) from the θ/δ_e and ϕ/δ_a Bode plots. These values depended on how much data was gathered with the frequency sweep (range of frequencies collected without tripping). Then, if the points were not consistent in bandwidth (frequency range from the gain or phase margin to the 180 degree crossover frequency), the values of measured average coupling changed. For example, if a trip was encountered during the sweep at 0.5 rad/sec causing a phase of 180 degrees, then it was near that frequency that the average coupling was measured, rather than the correct bandwidth of the aircraft for the appropriate coupled configuration. The ADS-33E-PRF (paragraph 3.4.5.4) method is therefore very sensitive to the phase portion of the θ/δ_e and ϕ/δ_a Bode plots.
- Second, the metric had no correlation to the pilot flying the aircraft: the bandwidths where the coupling was measured were solely aircraft dependent, and there was no guarantee that the frequency at which the pilot was making the inputs and from which the comments arose corresponded to the above bandwidths. As a result, pilot comments might be related to a different magnitude than the one measured by the metric and plotted on the chart. This was especially plausible since the pitch and roll bandwidths in the VISTA were different: the bandwidth of the aircraft in the pitch axis was found to be from 4 to 8 rad/sec, but the bandwidth in the roll axis was 1 to 5 rad/sec only. As already said, the pilot inputs that led to the comments might have been at an even different frequency than the two measured. (see Bode plots for the baseline on figures F-13 and F-14). There was some discussion about „adjusting“ the metric to consistently measure the

coupling in the frequency at which the pilot is dealing with the aircraft responses, however there was no adjustment to the metric for this test.

- Third, the metric was able to capture the higher „apparent“ coupling induced by the filters, although the „jerkiness“ of the aircraft response was highlighted only in pilot comments and was not evident in ADS-33E-PRF specification (paragraph 3.4.5.4) chart. The difference between the 5 rad/sec filter and the 10 rad/sec filter was evident to the pilot but was not apparent from chart analysis. *Further investigate the relationship between the bandwidth measured by the metric and the frequency of the filters, to see if a different design of both filters and the metric itself could lead to a better representation of these dynamics.*
- Fourth, bias scenarios were not clearly captured by the metric, although the analysis of these points was very limited.
- Fifth, an initial look into a PSD analysis of stick deflections suggested a solid correlation between pilot physical workload and the configuration flown. Also, the above correlation seemed to be consistent among the three pilots, while preserving the different background information about pilot training (i.e. low bandwidth versus high bandwidth flying of bombers versus fighters). *Recommend further investigation to evaluate PSD of stick deflections as a potential input in the metric to predicted handling qualities of coupled aircraft.*

Flying Qualities Analysis

The inherent coupling of the VISTA was not expected by the test team. Only a thorough analysis of the frequency sweeps, granted by the metric data reduction requirements, led to its identification and measurement. This was particularly true since the pilot rarely performed step-type maneuvers while aggressively tracking a target. The exact cause of the roll due to pitch could not be identified in the time frame allotted, but suggestions were made on possible VSS-trim interface issues, control surface rigging, airframe asymmetries, and especially gyroscopic effects of the engine. This last one seemed to be the most plausible. *Recommend investigating the exact cause of VISTA inherent coupling.* To do so, different engine settings could be used while performing the pitch sweeps. As previously said in this document, this behavior had no effect on pilot ratings and comments.

PIOR Analysis

The first three handling qualities flights resulted in the general conclusion that stick and rate cross-coupling tended to produce undesired motions. As a general rule, PIORs tended to increase as the amount of cross-coupling generated for each configuration increased. Level I CHRs corresponded to PIORs ranging from 1-3, level II CHRs generated PIORs between 2-4; and level III CHRs corresponded to PIORs ranging from 2-6. During the initial handling qualities flights, it was difficult for the evaluation pilots to assess if the oscillations were a function of the desired cross-coupling or if the pilot was part of the oscillations. The basic PIOR scale utilized for the first handling qualities flights provided a usable outline, but failed to generate much clarification

real time in the aircraft. The PIOR scale available in the MIL-STD-1797B provided clarification for delineation between ratings of 2 and 3 that was not available in the basic PIOR scale. For example, a PIOR of 2 was associated with “undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique”. This reference was much more useful than the outline that simply asks if undesirable motion tended to occur or was easily induced. The line between a PIOR of 4 versus 5 was also clarified in the MIL-STD-1797B PIOR scale by the use of the word “divergent” to describe the different types of oscillations required for a PIOR of 5. The type and amount of compensation related to the oscillation helped define the type of PIOR appropriate for the configuration. For a PIOR of 4 the pilot must “reduce gain or abandon task to recover”, and a PIOR of 5 specified that “pilot must open the loop by releasing or freezing the stick”. Use of the MIL-STD-1797B PIOR scale was extremely helpful in defining the type of undesirable motion or oscillation experienced during the evaluations of each cross-coupling configuration.

This page was intentionally left blank.

APPENDIX Q: DATA PACKAGE DESCRIPTION

The data package consists of the following:

- Data
 - Sim PTIs
 - Baseline
 - Filters / Bias
 - Rate
 - Stick
 - Sim Task
 - Sim data
 - Ground Checkout
 - Ground data
 - Flights
 - Flight test data
 - Icarus flight cards/data cards scans
 - Bode Plots
- Code
 - Closed Loop
 - Matlab codes for primary and secondary task
 - Open Loop
 - Matlab codes for Bode plots generation and charts production
- Misc Files
 - Flight test data summary
 - Scores summary
 - Sim data predicted regions
 - Gains table
 - Freq sweep table
 - TIM
 - Test plan
 - Icarus Software

This page was intentionally left blank.

APPENDIX R: COOPER-HARPER RATING SCALE

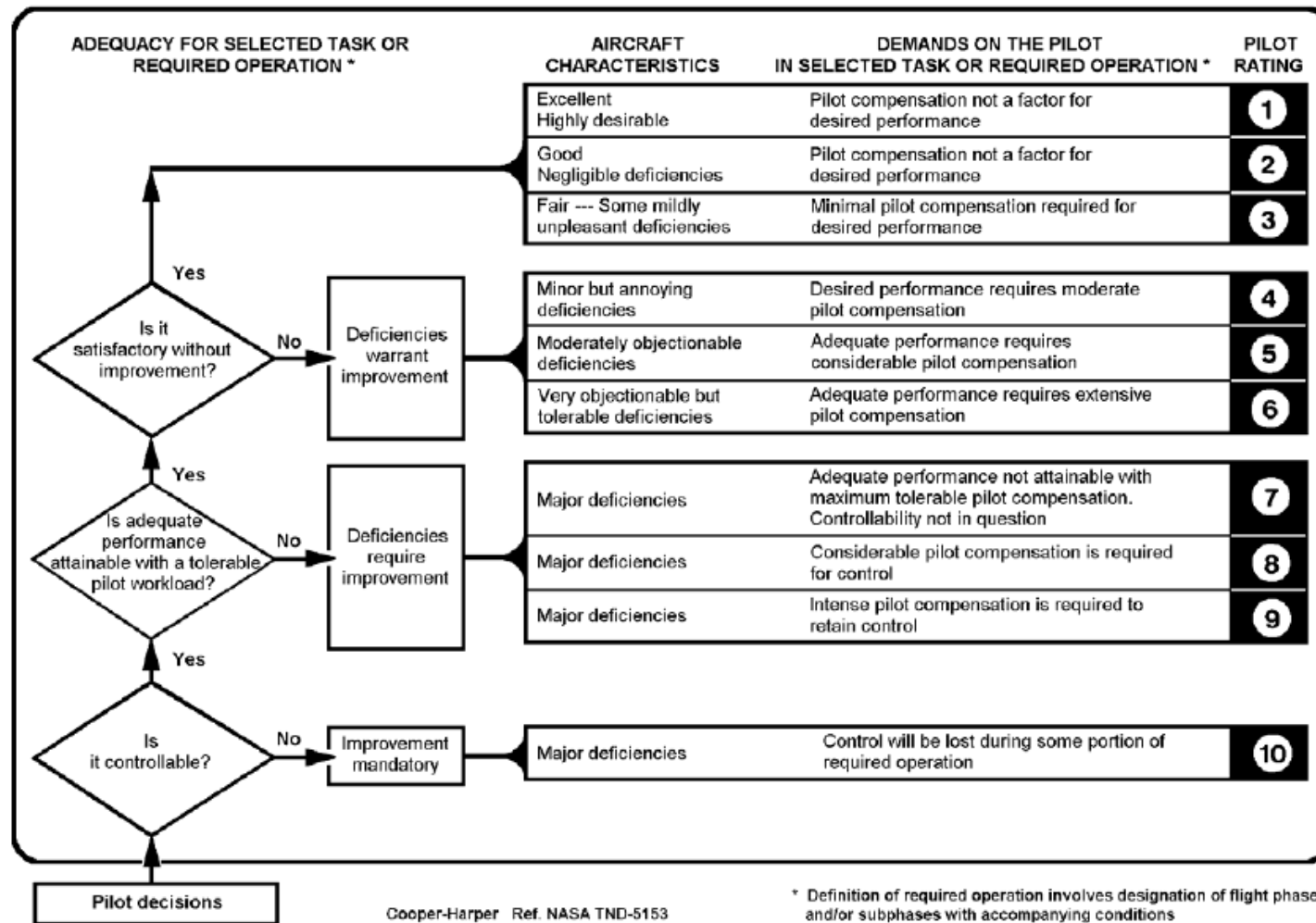


Figure R-1. Cooper-Harper Rating Scale

This page was intentionally left blank.

APPENDIX S: PIO RATING SCALES

Did I experience PIO ?

No:

undesirable motion ?

no —————→ **1**

yes

tend to occur ? —→ **2**

easily induced ? —→ **3**

Yes:

abrupt or tight control ?

bounded ? —————→ **4**

divergent ? —————→ **5**

normal control ? —————→ **6**

Figure S-1. Basic PIOR Scale

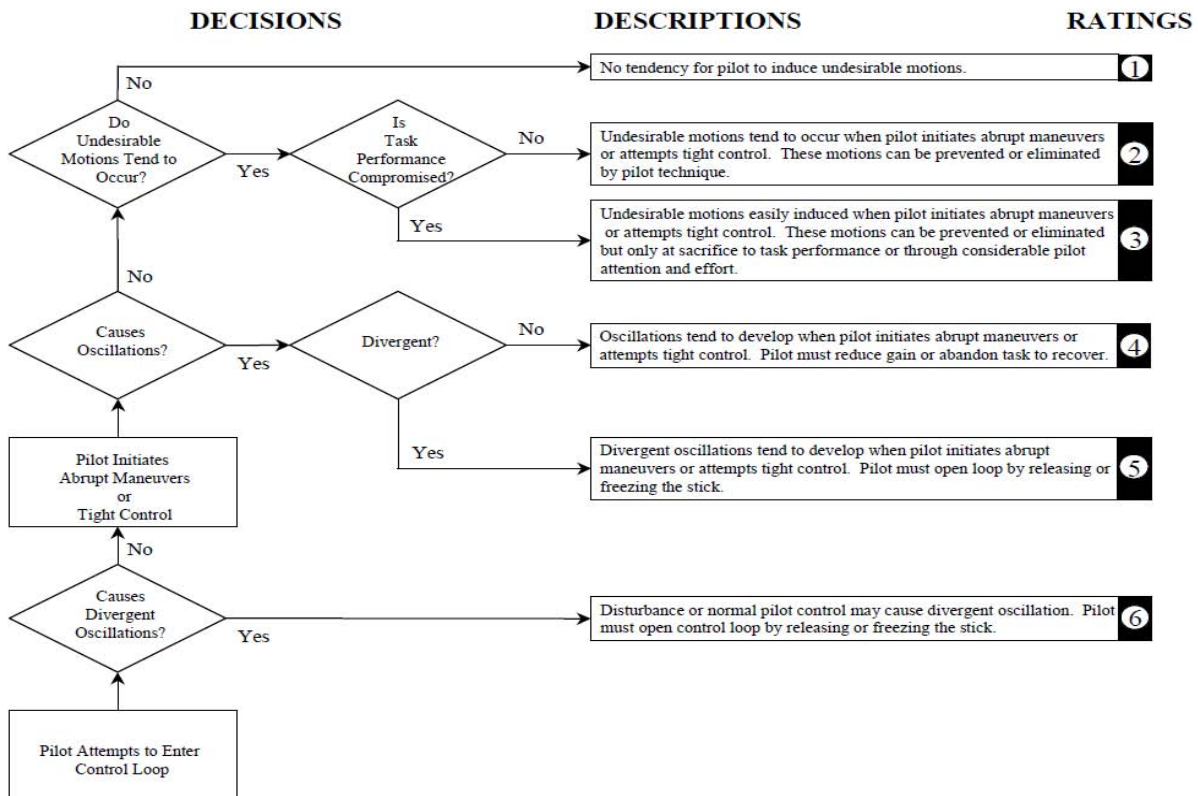


Figure S-2: MIL-STD-1797B PIOR Scale

This page was intentionally left blank.

APPENDIX T: LIST OF ACRONYMS AND SYMBOLS

AFFTC – Air Force Flight Test Center
AFFTCI – Air Force Flight Test Center Instruction
BW - Bandwidth
CCS – Configuration Control System
CHR – Cooper Harper Rating
 δ_{as} – Lateral stick deflection
 δ_{es} – Longitudinal stick deflection
dB – Decibel
DFLCC – Digital Flight Control Computer
FFT – Fast Fourier Transform
FPM – Flight Path Marker
FTE – Flight Test Engineer
HQ – Handling Qualities
HUD – Head Up Display
Hz – Hertz
KCAS – Knots Calibrated Air Speed
MFD – Multi-Function Display
 N_z – Vertical acceleration, load factor
 p – Roll Rate
 ϕ – Roll attitude
PA – Pressure Altitude
PIO – Pilot In the loop Oscillation
PIOR – PIO Rating
PSD – Power Spectral Density
PTI – Programmable Test Input
 q – Pitch Rate
SRB – Safety Review Board
 θ – Pitch attitude
TMP – Test Management Project
TPS – Test Pilot School
TRB – Technical Review Board
VISTA – Variable stability In-flight Simulator Test Aircraft
VIM – VISTA Integrity Monitor
VSS – VISTA Simulation System

This page was intentionally left blank.

APPENDIX U: DISTRIBUTION LIST

Onsite Distribution

	<u>Number of Copies</u>	
	Color Hard Copy	CD ROM (PDF)
USAF TPS/EDT 220 South Wolfe Ave Edwards, CA 93524	7	7
USAF TPS/CS (Attn: Dottie Meyer) 220 South Wolfe Ave Edwards, CA 93524	3	1
USAF TPS/DO (Attn: Bill Gray) 220 South Wolfe Ave Edwards, CA 93523	1	1
Fred Webster 773TS/ENFA Room 102 Building 1400 Edwards, CA 93524	2	2
412 TW/ENTL (AFFTC Technical Library) 307 E Popson Blvd, Bldg 1400, Room 110 Edwards AFB, CA 93524-6630	3	1
AFFTC/HO 305 E Popson Ave, Bldg 1405 Edwards AFB CA 93524-6630	1	1

Offsite Distribution

David G. Mitchell Technical Director Hoh Aeronautics, Inc. 2075 Palos Verdes Dr. North #217 Lomita, CA 90717	2	1
Mr. Bruce Cogan NASA Dryden Flight Research Center PO Box 273 Edwards, CA 93523	5	2
Defense Technical Information Center DTIC/OMI 8725 John J. Kingman Road, Suite 0944 Ft. Belvoir VA 22060-6218	1	1

Total	25	17
-------	----	----